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Final Scientific Report

SITE SELECTION FOR A SEISMIC ARRAY STATION AND CRUSTAL STUDIES IN NORWAY 1965

1 April 1965 — 31 December 1966

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SITE SELECTION FOR A SEISMIC ARRAY STATION AND CRUSTAL STUDIES IN NORWAY 1965

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PART I

SITE SELECTION FOR A SEISMIC ARRAY STATION IN SOUTH-CENTRAL NORWAY

by

ANDERS SØRNES

ABSTRACT

The different seismic aspects involved in a possible relocation of the LRSM array station near Lillehammer are investigated. The magnitude station factor is found to be -0.1 for both the Lillehammer array station and the Kongsberg WWSSN – station. Short descriptions are given of three new potential sites found by a field inspection survey. Results from continuous recordings of earthquakes and noise for several weeks at these sites are given and compared. It is concluded that one of the new potential sites, Sinkerud, should be preferred among the sites considered.

FOREWORD

The author wishes to express his sincere thanks to the following persons. Dr. P. L. Willmore of Royal Observatory, Edinburgh, for more than two months put to the free disposal for this project two complete field recording instrumentations, including play-back and transportation facilities and an experienced maintenance technician. This technician, Mr. G. Andersen, and Mr. O. Fuhr undertook the field recording. Mr. T. Birkeland, geologist, participated in the preliminary field survey. Mr. R. Parks of Royal Observatory, Edinburgh, has performed the frequency analysis. Mr. E. Sundvor has assisted in working out of all data. Miss E. Irgens has drawn all figures.

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INTRODUCTION

In order to improve the methods of detection of underground nuclear explosions to such a level that these tests could be included more easily in a test ban treaty, the Advanced Research Project Agency (ARPA) in Washington sponsores a number of research and development programs. One of these programs, the Long Range Seismic Measurement (LRSM) program, included the setting up and the operation of about forty seismic array stations. The intention of this program was to collect comparative recordings of earthquakes and explosions. The American underground test series planned at that time offered the necessary events with known parameters. One of these stations started recording in Norway in August, 1963, and was then called 00 NW Oslo. The Geotechnical Corporation undertook the instalation of the station and also the operation of it until 1 April, 1965. At that date the operation of the station, now called LHN Lillehammer, was taken over by the Seismological Observatory, University of Bergen, on an ARPA research contract expiring 31 December, 1966.

The seismic array station set up in Norway was a mobile station and, therefore, was not installed as would be a permanent one. For example, the recording equipment is still housed in a trailer. The site selection had to be made without a thorough survey in order to be able to keep the time schedule. The title to the instrumentation is now transferred to the University of Bergen which will operate the station on a permanent basis in the future. Therefore, we face the question wether the station shall be made into a permanent installation at the present site or be moved to another site if this is found to be worth while.

This report summarizes data on some important questions relevant to the problem of a possible relocation of the Lillehammer array station. The station and its present site are described elsewhere; therefore, only a short description will be given in this report. The results of a field survey to select potential new sites follows, taking into consideration geology, topography, accesibilities, power, etc. Afterwards, the results of noise measurements at the three selected sites are given. An investigation of the signal-noise ratio at sites in south-central Norway follows. Next some results of an investigation of the magnitude residuals in south-central Norway are given. The report ends with a closing discussion before conclusion.

THE LILLEHAMMER ARRAY STATION

The instrumentation and the site of the Lillehammer array station are described in another report which also contains some information on the background noise at the site (Geotechnical Corporation, 1964). For this reason, only a short description will be given here. The standard LRSM seismograph system consists of a three component short-period Big Benioff seismometer set, operated at a natural

period of 1 second, and a Sprengnether long-period three component set, operated at a natural period of 20 seconds. The azimuthal orientation of the horizontal seismographs are 138°and 228°. In addition to the standard LRSM seismographs, a seven element linear crossed array of Big Benioff short-period vertical seismometers with a spacing of one kilometer is installed. All seismometers except Z-2 are placed in tank vaults which are buried in 4 feet excavations. At Z-2 the vault is set on the surface of an exposed outcrop. For all seismometers are used phototube amplifiers having a galvanometer with a natural period of 0.2 second and 30 seconds for the short- and long-period seismometers respectively.

The recording system consists of one Develocorder, recording on 16 mm film; two four-channel 35 mm Film Recorder; one Helicorder, recording two channels on heat-sensitive paper; and one Amplex 14 channel magnetic tape recorder, producing FM modulated 1-inch wide magnetic tapes conforming to IRIG standards. The basic information required for interpreting the data recorded at the LRSM-stations is given elsewhere (Geotechnical Corporation, 1962). The recording system of the Lillehammer station is modified to accomodate the array data. The array data is recorded on the Develocorder and on the magnetic tape. The accomodation of the array data on the magnetic tape is achieved by not recording the LRSM data with two different gain levels which is the standard procedure. This practice is lowering the dynamic range of the LRSM data by 20 db.

The topography and the array lay-out of the present site are shown in Fig. I-1. The area of the site is covered by a map on scale 1:50000 contour interval 20 m (Series M-711 no. 1917 IV Åsmarka). The quaternary geology maps is shown in Fig. I-2. This map and the other quaternary geology maps in this report are redrawn after the geology edition of " Landgeneralkart over Norge " published by the Geological Survey of Norway, original scale 1:250000. The topography on all maps shown in this report are drawn from " Gradtegnskart " or " Rektangelkart ", whichever covers the area, published by by the Geographical Survey of Norway, original scale 1:100000, contour interval 30 m. Greater parts shown on maps in this report are also covered by more recently published maps on greater scales, mostly 1:50000, and smaller areas even on greater scales. For the sake of homogeneity in comparison the topography maps are all drawn from the maps mentioned above originally on scale 1:100000.

An index map showing the location of all sites in Norway mentioned in the closing discussion are given in Fig. I- 17.

The coordinates of the present array cross point Z - 2 and of the LRSM vaults Z - 3 are:

Z - 2 : 61° 03' 17'' N 10° 51' 58'' E

Z - 3 : 61° 02' 57'' N 10° 52' 48'' E

The standard bulletin data which we are issuing, refer to Z - 3. The array vault elevations are as follows:

Z - 1	547 meters ;	Z - 2	555 meters;
Z - 3	505 "	Z - 4	484 "
Z - 5	556 "	Z - 6	503 "
Z - 7	469 "		

In this area the metamorphic Precambrian rocks are overlain by Eocambrian (early Cambrian) rocks. The bottom strata is called Brøttum sparagmite, which is a dark grey rock with intercalations of arenaceous shale. These strata may be about 1000 m thick. Next in the sequence is the Biri conglomerate followed by Biri limestone. These strata are followed by Moelv quartzite conglomerate and Ekre sandstone. At vault Z - 2 there was an exposure of sparagmite. The vault Z - 3 is excavated in a thin bedded, severely weathered slate; but the rock becomes fairly hard and competent at a depth of about 4 feet. The rest of the vaults are buried in brown, unconsolidated, unsorted glacial deposits, ranging in size from sand to boulders. The drift is Pleistocene in age. During November, 1966, a field survey was carried out to find the thickness of these thin glacial deposits by seismic methods for the vaults not placed on rocks. This survey also provided the average velocities in the deposits and in the bedrocks beneath. For the vaults in the glacial deposits the following results were found:

Vault	Z-1	Z-4	Z-5	Z-6	Z-7
Thickness of upper layer in meters	24	21	7	20	14
Avg. velocity in upper layer in m/sec.	1950	2100	1710	1200	1980
" " in bedrock in m/sec.	4540	4180	4160	4160	4950

Th   eas of the array are forest land, partially cut over, leaving scattered clearings and tracks in the evergreen timber.

FIELD SURVEY

During two weeks in September, 1966, 13 potential new sites in south-central Norway for the Lillehammer array station were inspected by the present writer and cand. mag. Tore Birkeland, geologist from the University of Oslo and responsible for the geological evaluation. Some other sites were considered at an earlier stage, but they were rejected after map studies. The most important features which were evaluated from maps were topography, accessibi-

lity, power supply, geological condition, and remoteness from sources of cultural noise.

The field survey was performed mostly by driving about in our Volkswagen bus, but some areas had to be inspected mostly on foot. During the field survey all except two relevant aspects were considered with regard to the usefulness of each site. The two aspects not considered were the economics involved in the establishing of an array station at the different sites and the possibilities for renting land. These aspects are very much connected. It was impossible to investigate these questions because they acquired too much time. Also most of the potential sites which were visited would be rejected after this field survey and much work would be spent to no use. Therefore, this report is concerned only with the scientific questions involved; but, of course, the other questions were mentioned occasionally when speaking to local people. The aspects not considered here are most efficiently dealt with in the final evaluation of a separate project to make the array station into a permanent installation at a selected site among the few for which the scientific aspects are discussed in the present report.

The findings during this field survey are given in the day to day journal for the survey. All this detailed discussion will not be quoted here. The conclusion, however, was that out of the 13 inspected potential sites, 3 seemed to offer better conditions than the other 10. These 3 sites will be presented here with one map giving the same sort of information as an ordinary topographic map and another map showing the quaternary geology which in these areas gives information of just the superficial layers. The much older bedrock beneath is briefly described in the following paragraphs, one for each of the three sites.

The name and position for each site are chosen to be the same as the places where the noise measurements were performed. No array lay-out is drawn on the maps of the potential sites because the new array pattern and its dimensions are not yet chosen, and a definite placing must wait until the final evaluation of the site. All private roads in the areas are not drawn on the maps mostly because they are not kept open during the winter.

Sinkerud (SIR), 60° 00' 17.8'' N 11° 38' 57.7'' E h = 302 m.

Fig. I-3 and I-4 show the topography and the quaternary geology. The surface layers of loose sediments seemed to be of small thickness and the bedrock showed up as out-crops over the whole area. By moving an array pattern about short distances it is believed that it will be easy to dig vaults for surface seismometers down to bedrock. Much of the area is used as productive forest land. Sinkerud has electricity, and the road from the south is open all winter.

Nearly all the area which is considered a potential site, is covered by a recently issued map (1963) on scale 1:50000, contour interval 20 m (series M-711 no. 2015 III Strøm).

In this area the bedrock is of Precambrian age and consists mostly of grey gneisses of variable composition with minor zones of amphibolite. Gneisses with hornblende and garnet alternate with biotite-rich gneisses. Pegmatite appears in the southern parts of the area. The strike is mostly NW in the eastern parts, and the dip is approximately 55° against NE. Near the Floen-Dragsjø district the strike is more northerly, and the dip is less. The strike is variable along the lakes. A north-south fault probably runs along Floen-Dragsjø.

Aurtjern (AUT), 60° 29' 34.1" N 11° 44' 28.1" E h = 400 m.

Fig. I-5 shows the topography of this site, and Fig. I-6 shows the quaternary geology. Here also thin layers of loose sediments are present. Greater parts of the area are productive forest land. Maps specially made for the local forest administration on scale 1 : 25000 with contour interval 10 m, partly cover the area.

The road from Mo, passing Aurtjern eastward, is kept open most of the winter, and it should be easy to keep it open all winter. Aurtjern has no electric power, but at several other places power lines extend into this area. A high voltage power line passes east-west some three km north of Aurtjern.

Granite is the dominating rock type in this district. The granite is mostly coarse-grained with the minerals mikrokline, plagioclase, and quartz, less mica. Remnants of basic rocks and fine-grained gneisses are lying in the granite. A gabbromassif is lying south-east of Lake Fløiten.

After the formation of granite a schistosity-zone was formed. This zone extends northward from a point 1 km west of Elgsjø where the zone is very narrow. The zone passes 1 km west of Aurtjern where the zone is approximately 2 km wide. The rocks change gradually from granite to augen-gneiss to mylonite in this zone. A fault goes north-south along Tannåa; otherwise, the district is little tectonized.

Sørbekksæter (SØS), 60° 36' 19.2" N 09° 52' 39.1" E h = 929 m.

Fig. I-7 shows the topography and Fig. I-8 shows the quaternary geology of this site. The superficial layers of loose sediments are very thin in this area. The road to Sørbekksæter is open all winter. Electric power is also available at Sørbekksæter, but the telephone line to the place is private and very poor.

This area is lying completely within the "Flå-granite". The southeastern parts consists of fine-grained quartz-monzonite. The rest of the area consists of porphyric quartz-monzonite. The porphyric quartz-monzonite is probably younger than the fine-grained variety.

Small fragments of gneis appear occasionally. Smaller bodies of fine grained quartz-monzonite are lying within the porphyric variety and vice versa. The foliation is most common in the porphyric variety. No majore fractures occur in the area.

NOISE MEASUREMENT AT THE THREE SELECTED SITES

Two portable tape recorders complete for independent recording at sites without power supply were put to our disposal by Dr. P. L. Willmore of Royal Observatory, Edinburgh. One technician from Royal Observatory, Mr. George Anderson, brought these two recorders to Norway by boat in a Land-Rover with a 2-wheeled trailer on 4 November, 1965. Mr. Anderson was in charge of servicing the recorders on the expedition in Norway. He returned to Scotland with the instruments by boat on 12 January, 1966. The time of recording at each site varied from about 3 to 5 weeks depending on the recording time wasted because of malfunctions.

The Land-Rover soon proved to be very useful in the deep snow encountered, because of its 4-wheel drive. It also had a built- in engine-driven 3kVA alternator for battery charging at the site which at present had no power. The field recorders were battery-operated FM tape-recorders, a modification of a commercial unit from Thermionic Products Ltd. They were recording at 0.133 ips with a carrier of 120 cps giving the IRIG standard packing density of 900 cps, using 33% as the maximum frequency deviation. The tape width was 1 inch, and the recording head was a 16-track in-line head to SBAC specifications. All reproduce tape decks for 1-inch tape to IRIG specification with option of this 16- track reproduce-head are, therefore, able to reproduce the recordings. The recorders had 6 channels of recording electronics. One channel is used for a digital time code, one for flutter correction, and four seismic channels. The seismometers were Willmore Mark II, adjusted to 1 cps and operated as a three-component set rather near the recorder and the fourth seismic channel was used as an option for experiments with a vertical seismometer at a distance. As only 6 channels were recording at the same time, the tape was turned and also recorded on in the other direction. The tape had to be turned or changed every second day. The batteries usually last for two days under normal temperatures, but during winter operations they where changed each day. This caused no extra work, as the recorders were attended to each day for calibration.

The seismometers were placed in pits which were dug down to hard bedrock at places where the soil--cover was about 0.8 meter thick, and were as far away as possible from local noise sources. The bottom of each pit was made horizontal by pouring a concrete slab. Half the cylindrical part of a metal barrel with a diameter of 0.8 meter was placed in the wet concrete, making the pit into a cy-

lindrical vault. The unused half-stamped bottom part of the barrel was put on top as a lid, not reaching the level of the surrounding soil. Boards were laid across the pit, making the inside of the vault free from wind.

Fig. I-9 shows the results of a frequency analysis of data recorded at the three new potential sites. The tapes were speeded up 225 times, and the data from the vertical seismometer analysed through a Brüel & Kjær audio-frequency spectrum analyser. The spectrum analysis was performed with a filter band-width of 1/6 octave. The readings were then adjusted to correspond to a band-width of 1/3 octave because some earlier investigations refer to this level. The analyser takes about one minute to go from 20 to 20000 cps. Playing back the tape at a speed of 30 inch/sec means that about four hours real-time elapse during one analysis run. Also the next four hours were analysed, and the mean of the two runs were taken. These two runs were also repeated for each tape, and this showed that no significant change in shape of the resulting curve occured during eight hours. The results are shown in Fig. I-9 after they have been transfered to an amplitude-frequency plot, using the system frequency response.

Two of the curves in Fig. I-9 refer to the same condition of microseismic background because the data were recorded at the same time. For Aurtjern the data were recorded another date. The microseismic background level both in the band-pass of the short-period and long-period vertical components at the WWN standard station Kongsberg (KON), also in the south-east Norway, was the same during the time intervals when the data used in Fig. I-9 were recorded. The microseismic background at Kongsberg is shown in Fig. I-10 a and b. The amplitudes given in Fig. I-10 are derived by the standard method of reading microseisms, which means that the amplitudes in the records are taken to be the mean value of the maximum amplitudes of five groups of the most predominant waves in the seismogram occuring in time intervals of 20 minutes, the intervals being symetrical about the exact hours 00, 06, 12 and 18 GMT. The periods are derived by taking the mean value of the periods of the five groups of waves used for the derivation of the amplitudes. Fig. I-10 shows how the general microseismic background varies with time. Also, the amplitudes read from the short-period vertical components in Fig. I-10 show large variations due to the microseismic storms. But for example the periods associated with the amplitudes of 7μ for the short-period component during the strong storm 30 November were 4,9 seconds. This sort of microseisms is easily filtered away during play-back using narrow band-pass filters when the short-period data from a station recording on tape is scanned for P-arrivals. This is now the routine for the tapes from the Lillehammer array station.

COMPARISON BETWEEN MEASURES FOR THE SIGNAL-NOISE RATIO

All data recorded from the vertical components at each new potential site have been played back through electronic Krohn - Hite filters, which made the band-pass in real-time very much the same as the band-pass of the short-period photographic paper seismograms from the Benioff seismographs of the WWN station standard-tape (KON) and of the short-period Benioff film seismograms used in the LRSM program (LHN). Fig. I-11 shows the different relative responses of these systems which are typical for the sort of standard instrumentations which should be used for reading amplitudes of P-signals for determination of body wave magnitude (m_b).

The quantity read on the seismograms used for magnitude determinations is proportional to the ground particle velocity, namely amplitude devided by period. This quantity has been read for all P-signals recorded at the new potential sites. The same quantity is also read for all these P-signals on the Kongsberg and Lillehammer seismograms.

The background noise recorded by the band-pass of the short-period component, in the absence of a microseismic storm, appears to have a period in the seismogram not much different from the period of the P-signal of a teleseism. By reading the amplitude and periods of the background noise in the short-period vertical seismogram we can derive the same quantity for the noise as the quantity proportional to the ground particle velocity used for the P-signal in magnitude calculations.

In this paper the quotient between the maximum particle velocity in the P-signal and in the noise immediately before the P-arrival is taken to be a measure for the signal-noise ratio. The standard conventions for reading amplitudes and periods in body wave magnitude determinations are used for the P-signals; and conventions analogous to the reading of microseisms are used for the noise readings, except that a shorter ime interval is used instead of the twenty minutes interval used for microseisms. Here only about a one minute interval was used.

Fig. I-12 shows a plot of the difference between this measure for signal-noise ratio calculated for Lillehammer minus the same ratio calculated for the Kongsberg and the three new potential sites. Kongsberg is included in the figure to show the data distribution for another nearby station with a well-known response curve for which more data were available in the same time interval. Positive values for this difference indicated that the signal-noise ratio for that earthquake at Lillehammer is higher than at the other sites indicated in the figures.

MAGNITUDE RESIDUALS IN SOUTH-CENTRAL NORWAY

A frequency plot of the residuals found is shown in Fig. I-13 as the magnitude observed at the Lillehammer array station minus the preliminary average magnitudes calculated on the data reported in the Earthquake Data Reports published by USCGS. Every earthquake reported by USCCS which was assigned a magnitude at four stations or more, falling within 0.7 of a magnitude unit from the average for these stations, were used. USCGS uses the magnitude for an earthquake at each station not having a time residual against the standard JB-tables for the P-arrival exceeding 10 seconds, but for this study all magnitudes calculated on P-arrivals, having a time residual exceeding 4.9 seconds, were excluded. The magnitudes for the Lillehammer station were taken from the bulletins published for the time interval August, 1963, to March, 1965. This left 444 earthquakes to be included.

A similar frequency plot for Kongsberg is shown in Fig. I-14, using 161 earthquakes from the bulletin for the year 1964.

Fig. I-13 and I-14 show that the station correction factor to use in calculating magnitudes from both these two stations in south-central Norway is -0,1. These well calibrated stations indicate that the seismic P-signals received in this area are slightly stronger than the world average.

Based on the same data as in Fig. I-13, the average time residuals against the USCGS average magnitudes are plotted in Fig. I-15. The numbers in brackets shown in the figure indicate the number of events which refer to each point. More positive time residuals for the magnitudes below a certain value might indicate the average point at which the first swing of the ground motion is masked by the noise in the seismogram. Fig. I-14 shows, however, only the general tendency that the higher the magnitude more negative the time residuals.

Fig. I-16 shows a prequency plot of the difference between the magnitude observed at Lillehammer and at Kongsberg and at the three new potential sites. Positive values indicate that a higher magnitude is found at Lillehammer than at the respective stations indicated in the figure.

DISCUSSION

The seismic field survey carried out at the present array site during October, 1966, confirmed our doubt that the array lay-out is well placed. Some vaults are placed in glacial deposits of maximum 24 meter thickness having an average P-wave velocity as low as 1200 m/sec at places. The bedrocks under the elements were found to have a velocity down to 4060 m/sec. Because of these low velocities and also because of the poor prospects to find a lay-out for an

extended array-pattern allowing all elements to be placed on bed-rock, comparison between the new potential sites is emphasized in the following discussion.

The three new potential sites selected during the field survey in September, 1965, all seem to offer better geological conditions over an area large enough to suite an array lay-out with a diameter of at least 10-15 km. Sinkerud, however, is the closest site to the open sea in the Skagerrak. Aurtjern is the site which offer less open road facilities in winter time and has at present only a high-voltage power line through the central area. Sørbekksæter has its disadvantage in the high topographical relief just to the south of the area and the rather high average elevation, making the winter conditions harder.

The comparison of the amplitude-frequency curves for the noise obtained at the three new potential sites shown in Fig. I-9 indicates that for the short-period noise Sinkerud is the quietest site, while Aurtjern is the noisiest site. Any difference for the long-period noise shown in Fig. I-9 is not important for the selection of a site for a short-period array. The data used here were recorded by seismometers with a free period of 1 second, and any instrumental difference might play a more important role for the derivation of amplitudes with periods of as much as 10 seconds. It is believed that amplitudes of long-period noise would not be much different at sites so near each other in south-central Norway.

Data on the distribution of short-period noise at several places in Norway, but not places near the sites considered there, were also obtained by U.S. Geological Survey during the seismic long range refraction program undertaken in cooperation with the present contract (Warrick, 1966; and Warrick and Plouff, 1966). Most of the data refer to rather quiet conditions during the time interval between 14 August to 3 September 1965. The conclusions from that low level short-period noise data were that no obvious correlation of noise level with major geologic province was found but that the highest noise levels are generally those nearest the western coastline.

The comparison between the signal-noise ratioes shown in Fig. I-12 indicate that among the new potential sites Sinkerud seem to be slightly better than the other sites. The comparison between the magnitudes in Fig. I-16 also show that Sinkerud is slightly better than the other new potential sites. One must, however, bear in mind that very little data became available during the short time of field recording and therefore no firm conclusion should be drawn from the above mentioned data alone.

CONCLUSION

The local logistics, the geology, and the limited seismic data presented in this report seem to indicate that Sinkerud should be prefered among the sites considered here. This site has, however, the shortest distance from the open sea in the Skagerrak. Because the available information does not indicate that this site is much better than the others, one should reconsider all sites once again if, following any future decision to investigate the cost of installing the station at Sinkerud, it appears that the renting of land, etc., is difficult or expensive.

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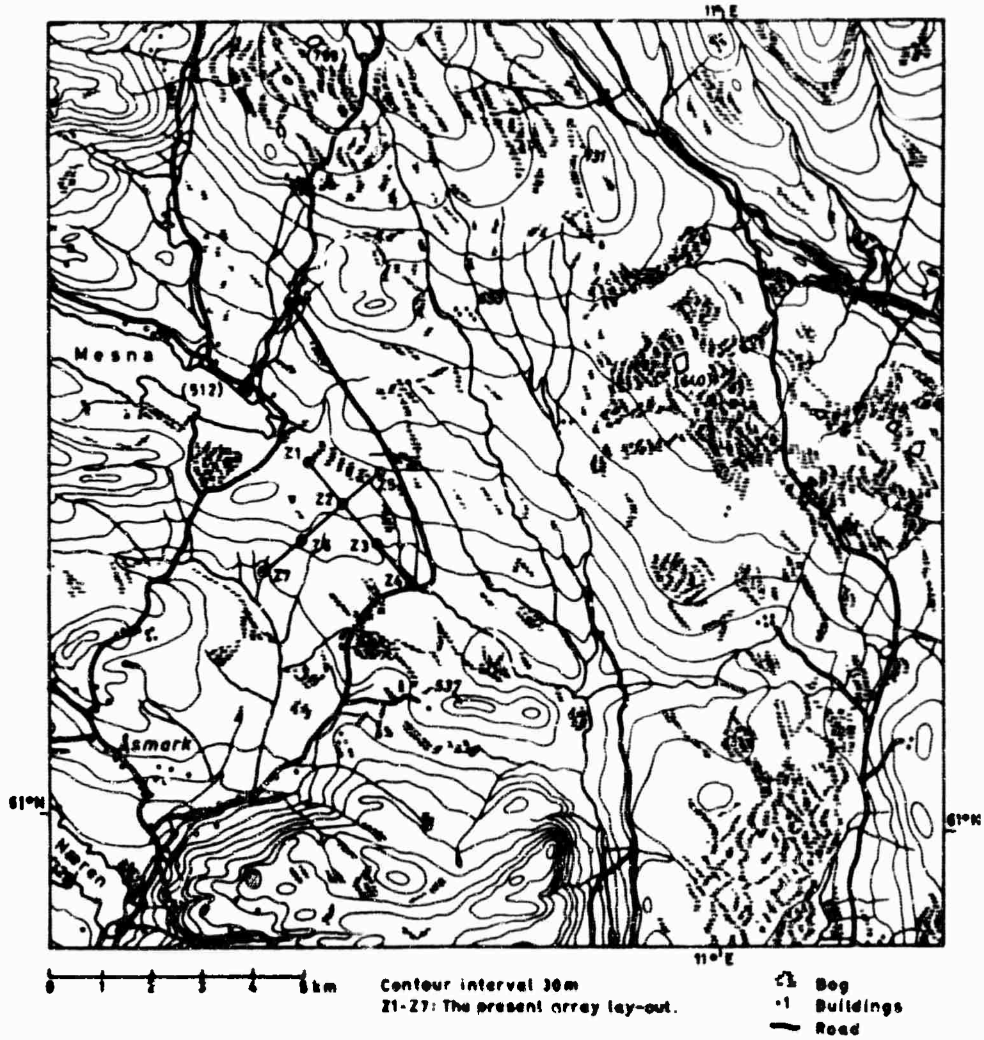


Fig. I - 1 Topography around the Lillehammer site.

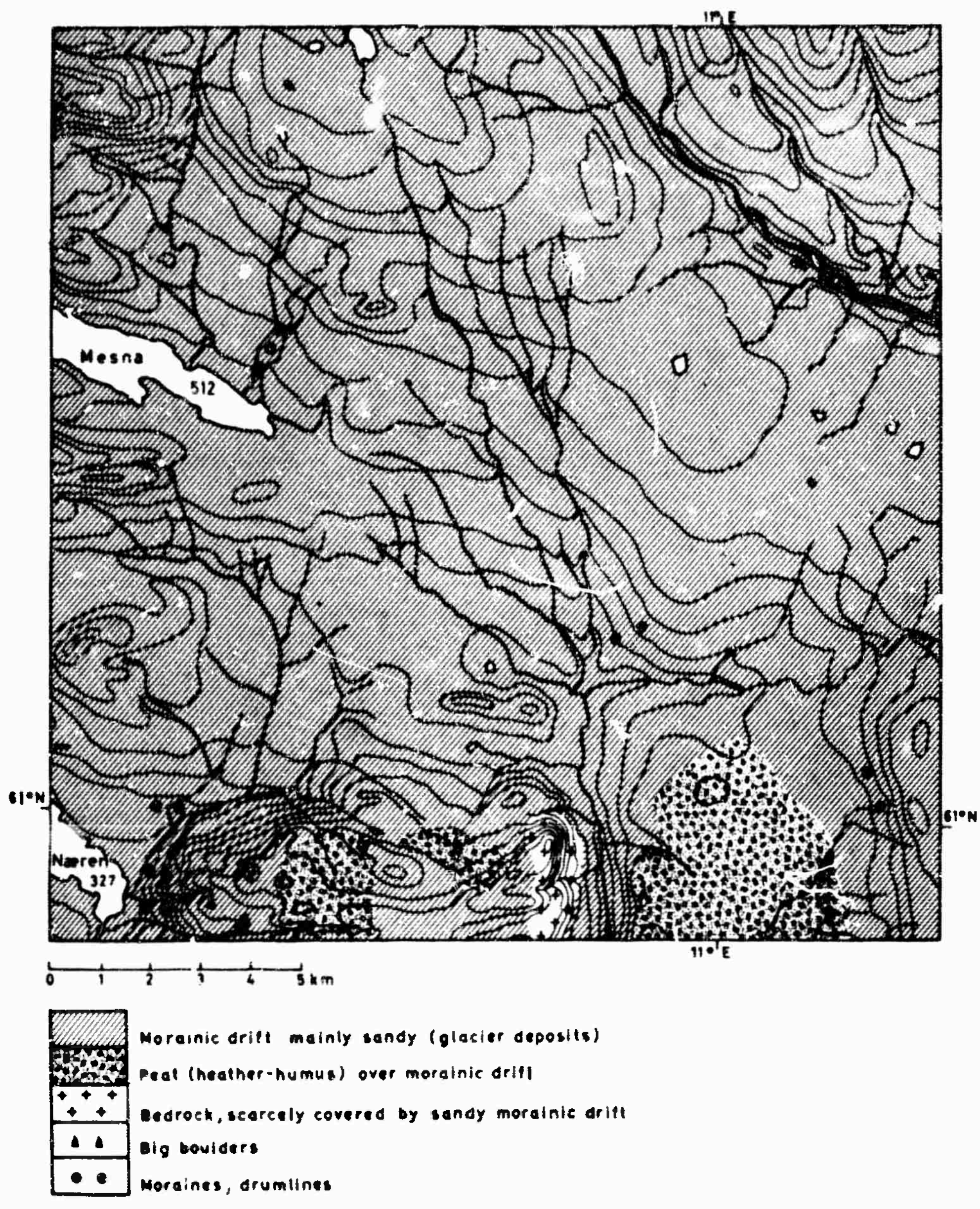


Fig. I - 2 Quaternary geology around the Lillehammer site.

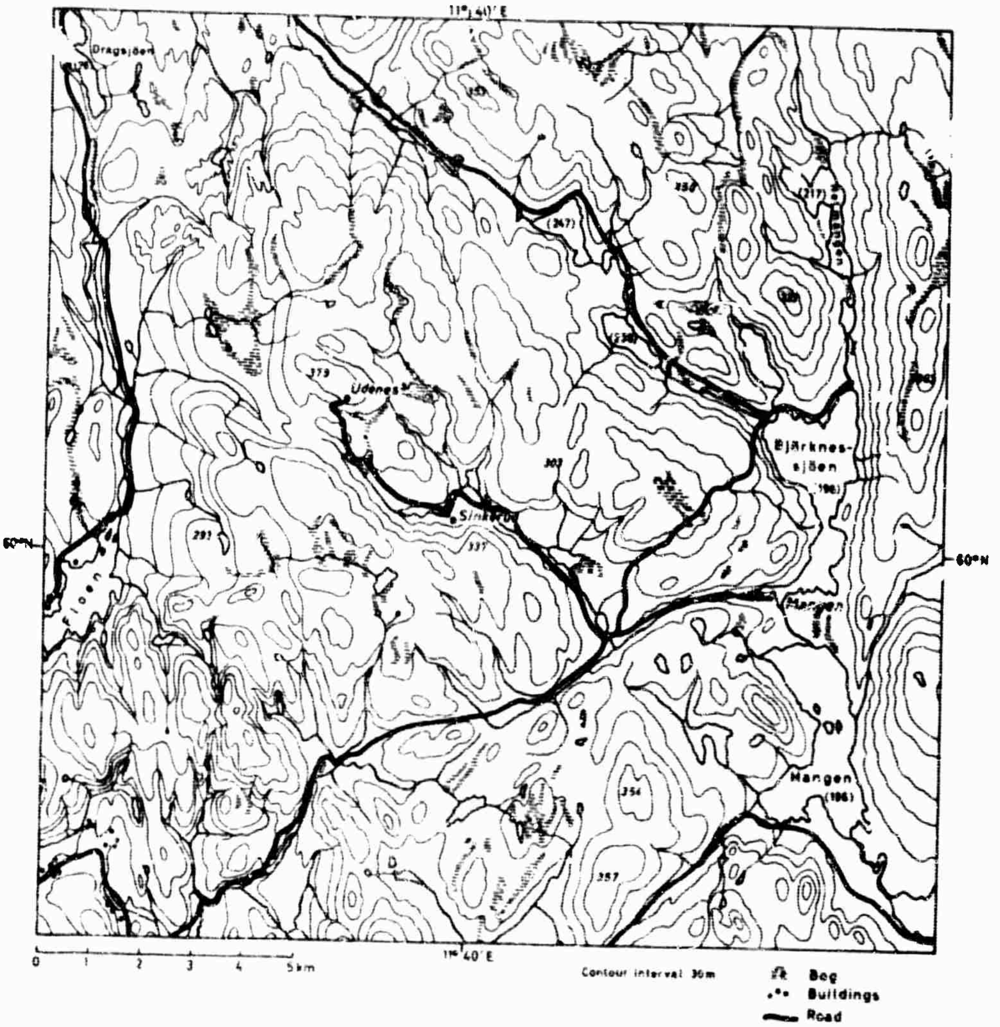


Fig. I - 3 Topography around Sinkerud.

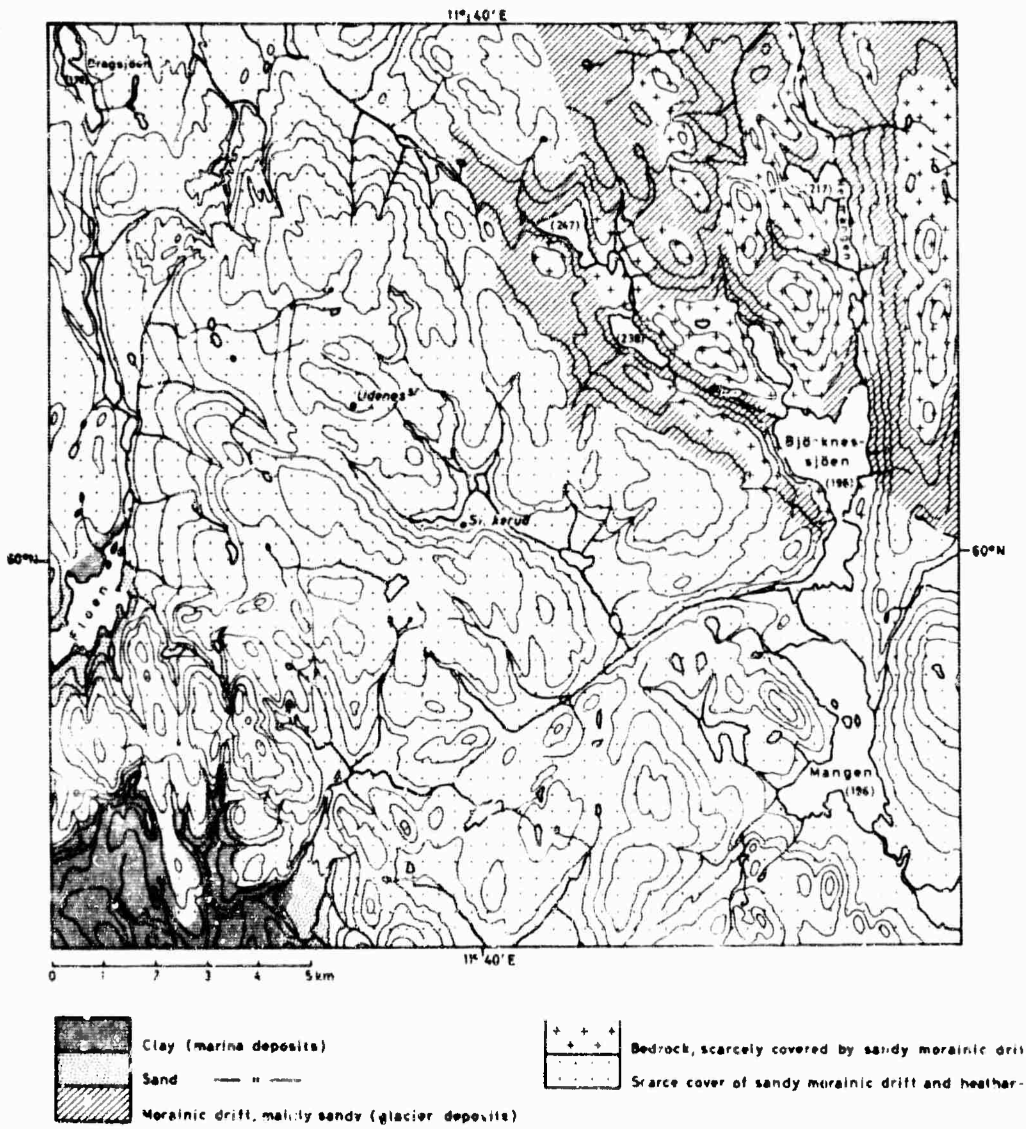


Fig. I - 4 Quaternary geology around Sinkerud.

Fig. I - 5 Topography around Aurtjern.

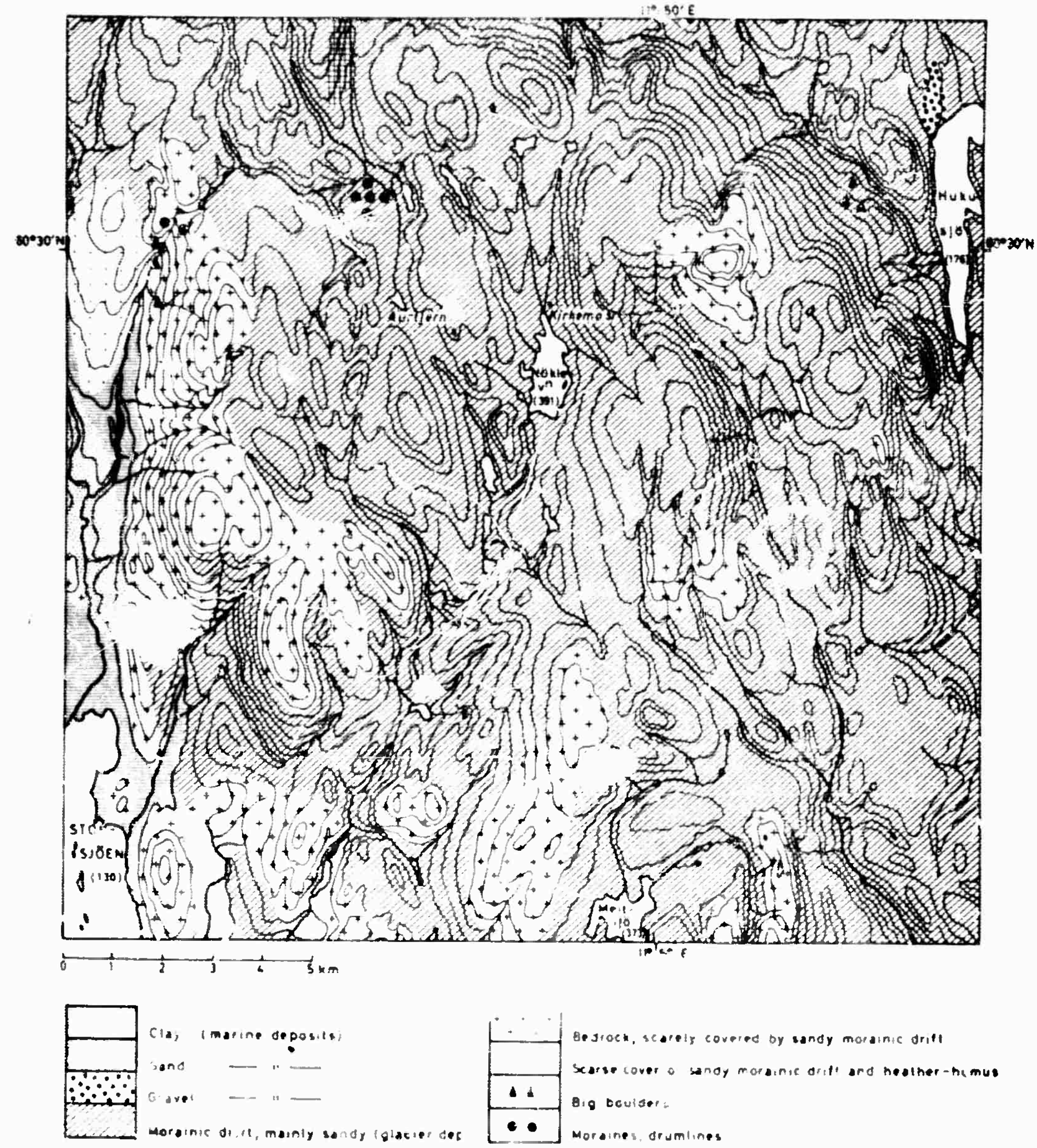


Fig. I - 6 Quaternary geology around Aurtjern.

Fig. I - 7 Topography around Sørbekksæter.

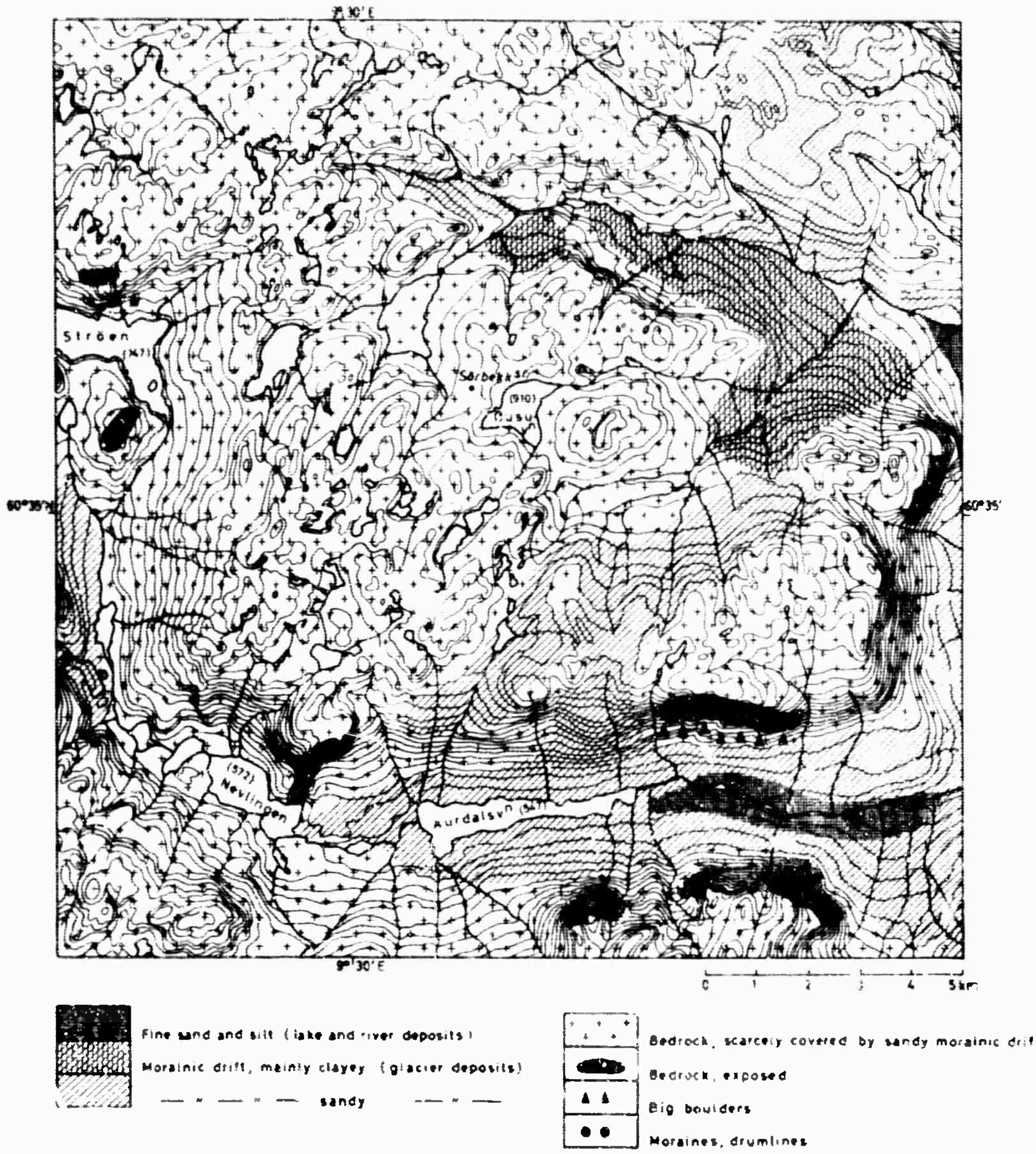


Fig. I - 8 Quaternary geology around Sørbekksæter.

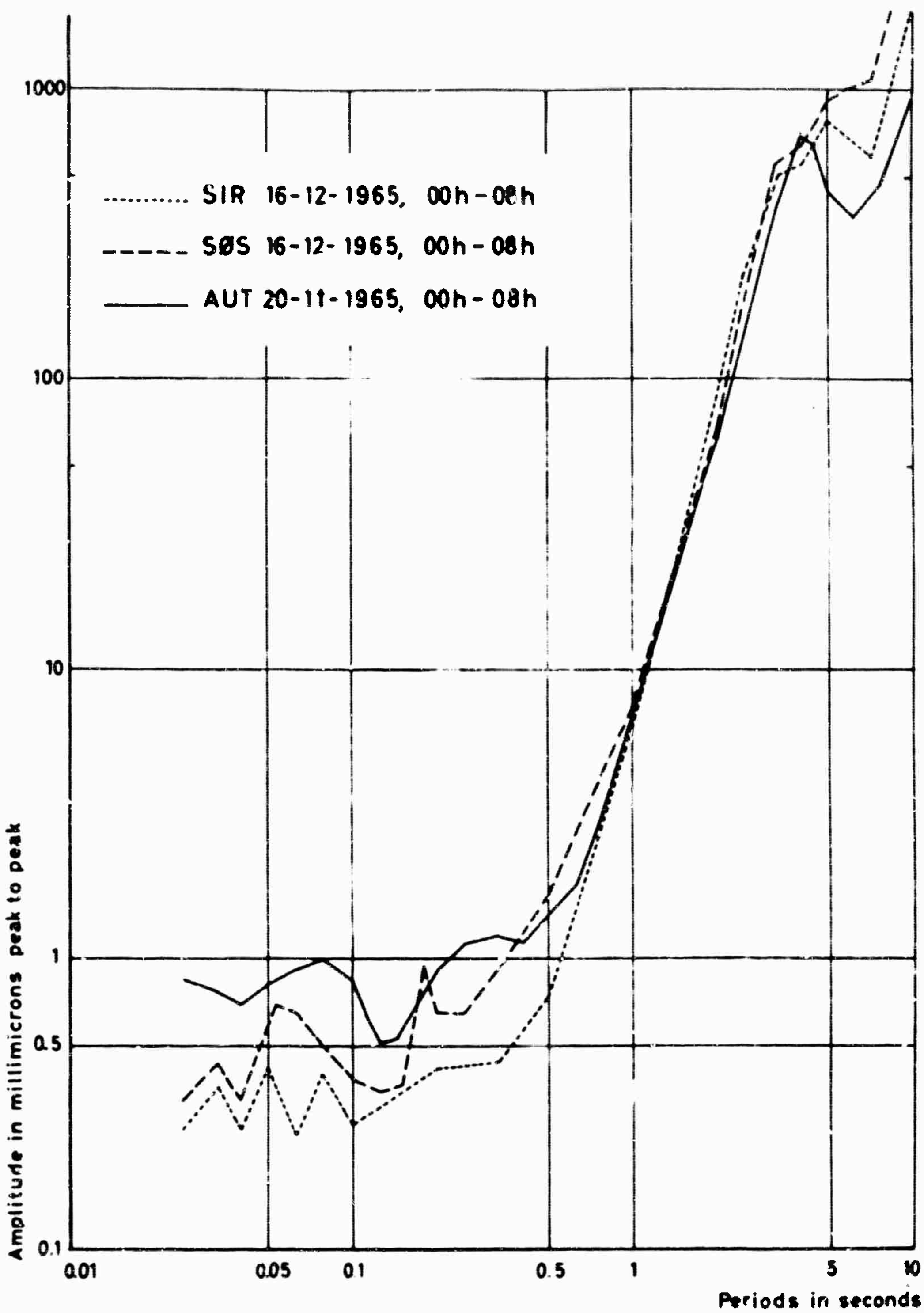


Fig. I - 9 The spectra of seismic noise recorded at the three new potential sites.

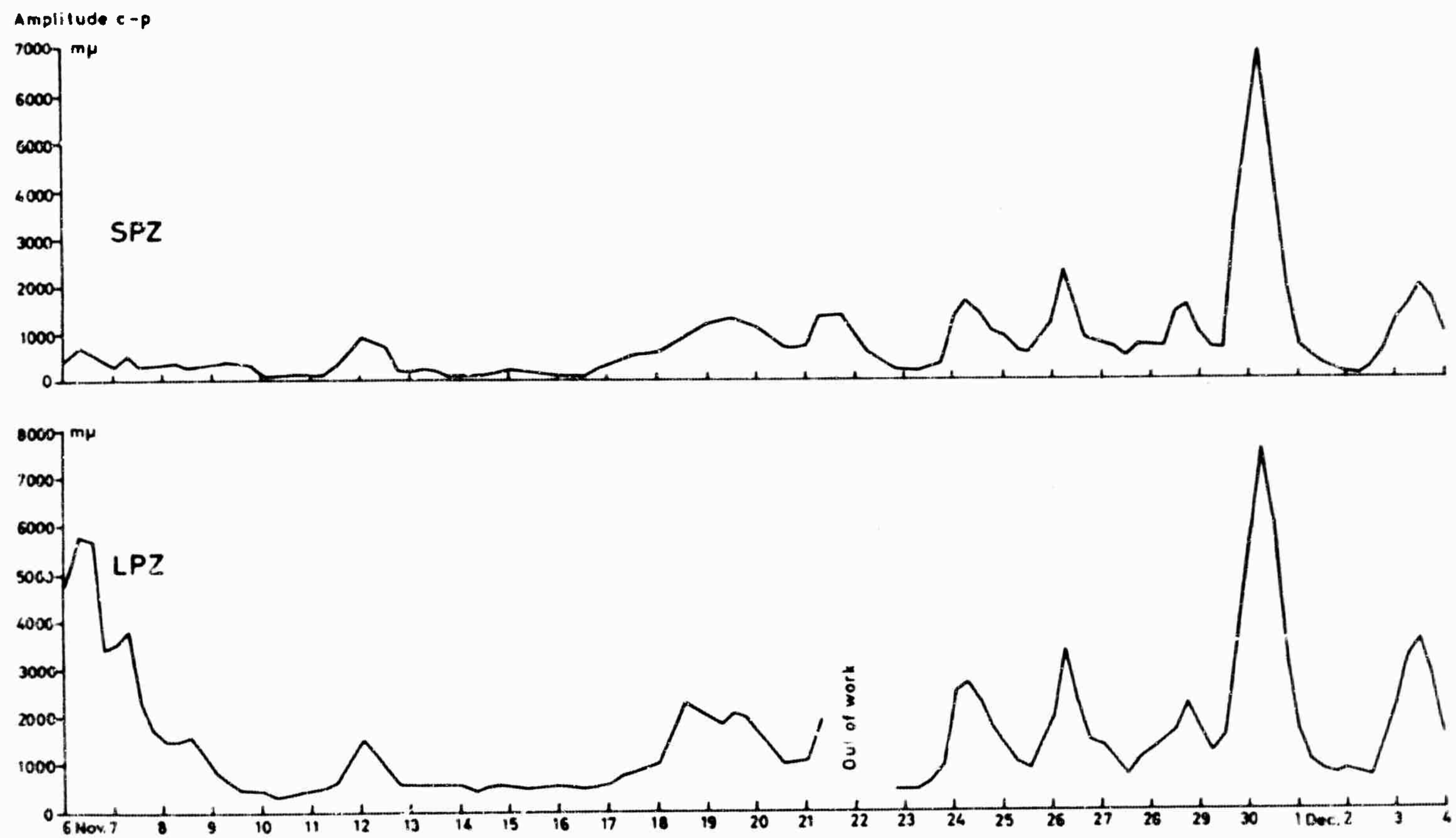


Fig. I -10 a Microseismic background at Kongsberg.

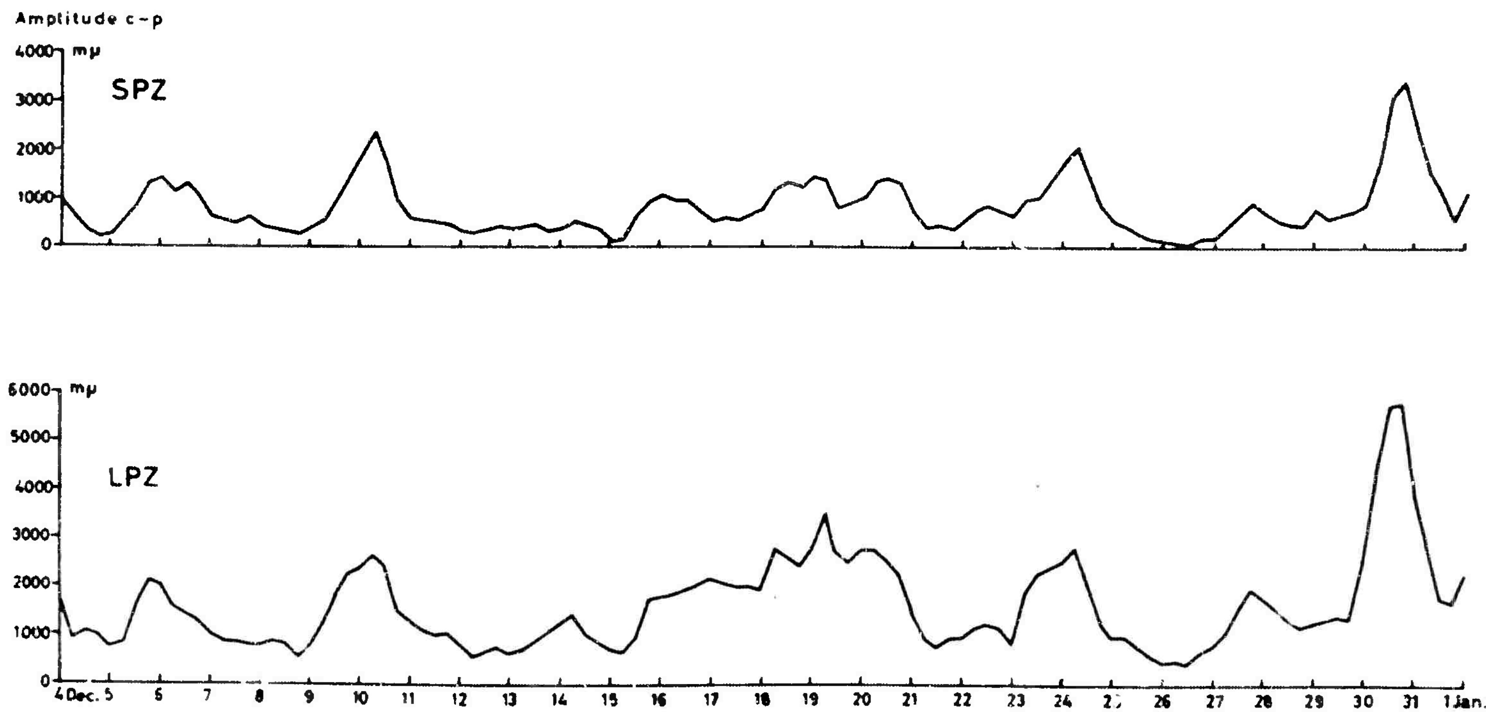


Fig. I -10 b Microseismic background at Kongsberg.

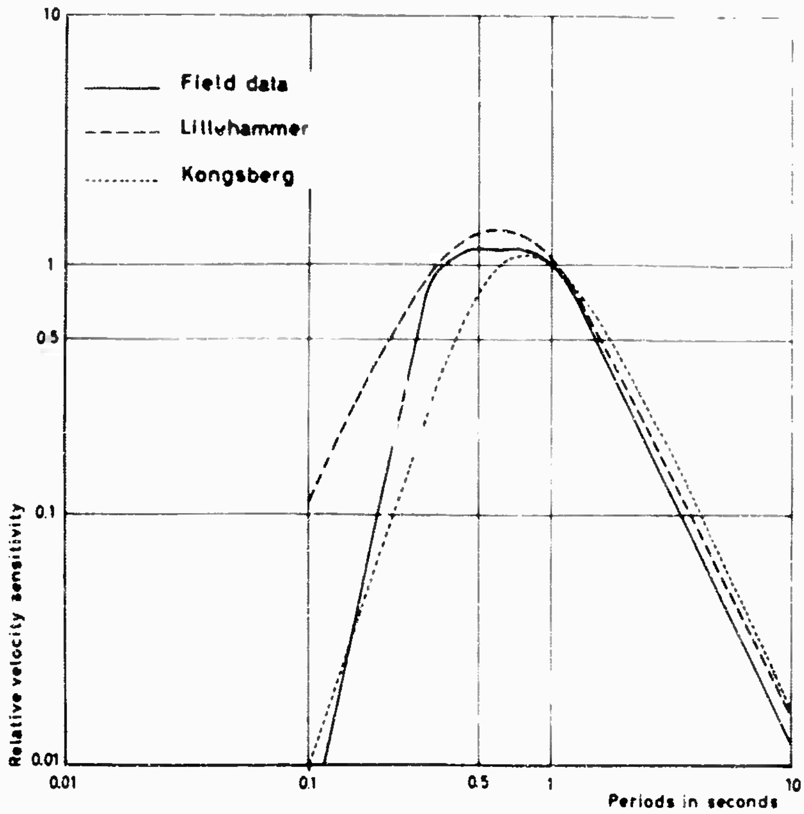
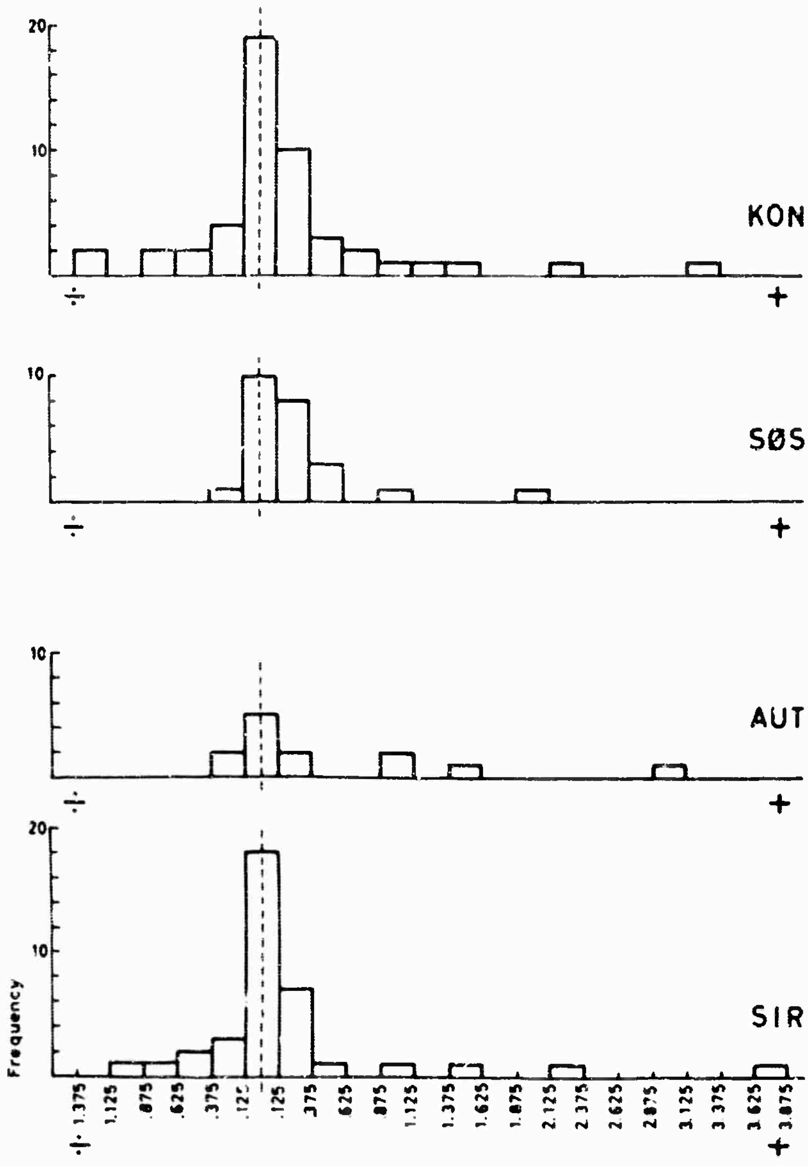


Fig. I -11 The relative response for the systems used.



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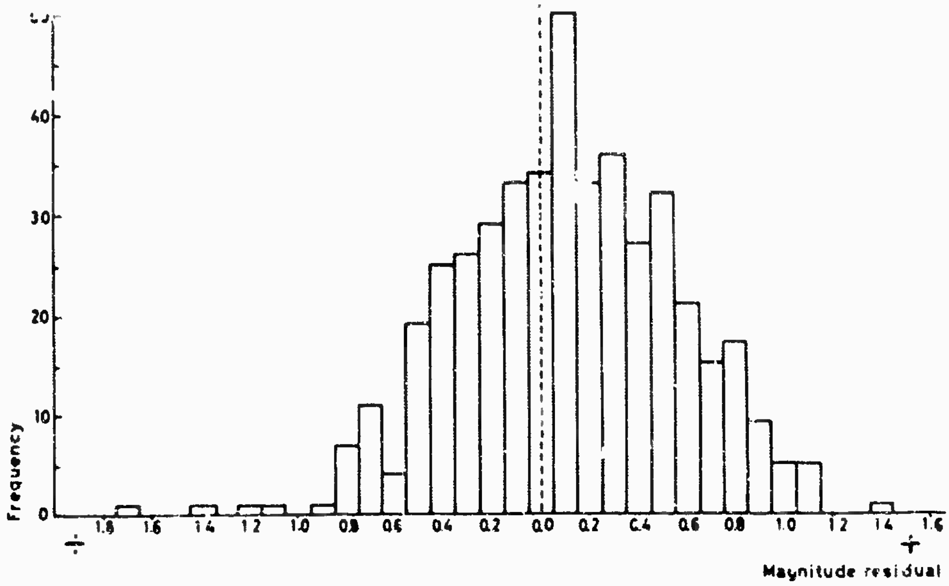
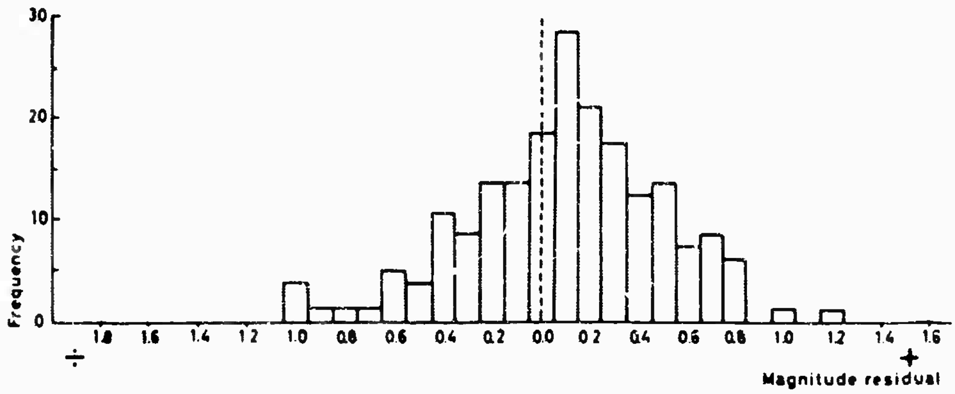


Fig. I -13 Frequency plot of the magnitude residuals at Lillehammer



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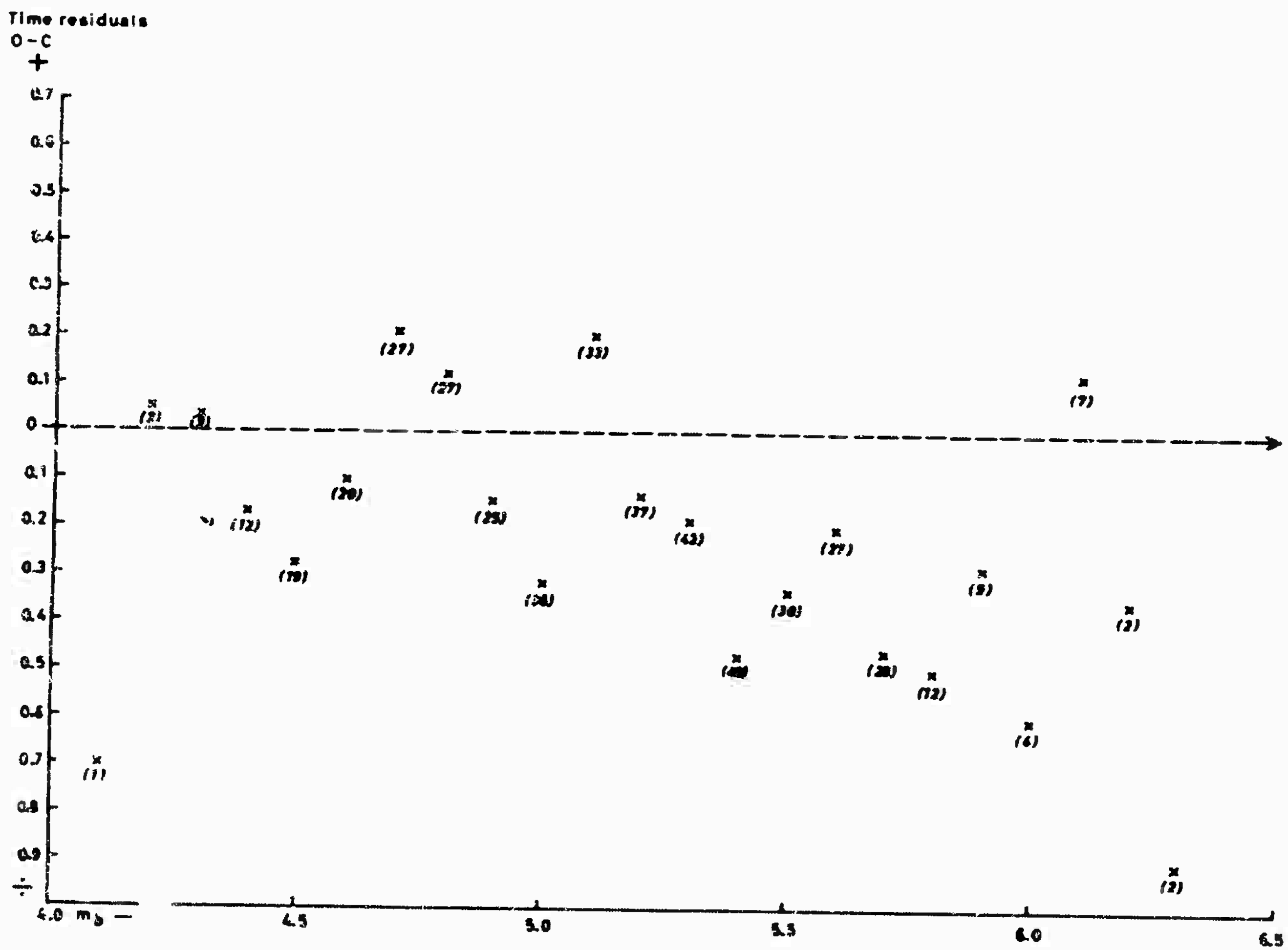

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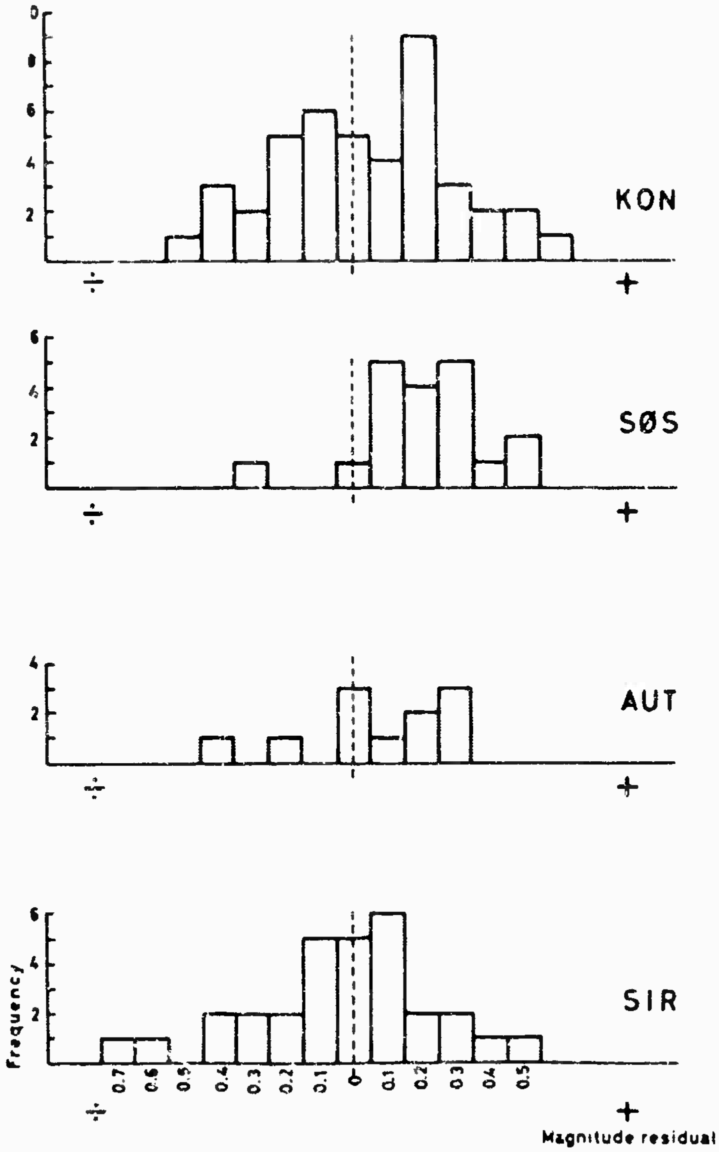

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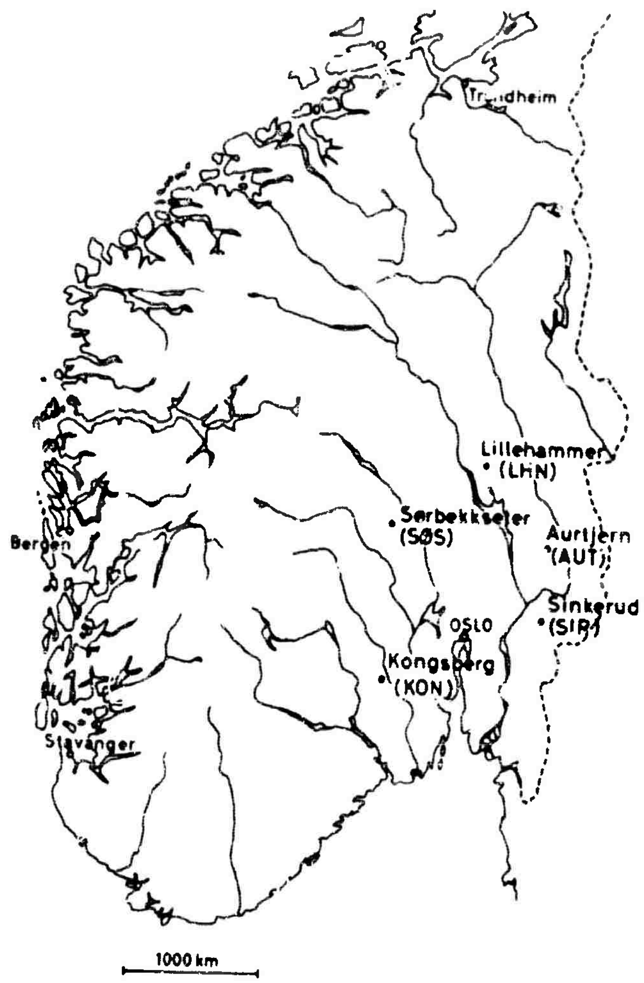

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PART II

CRUSTAL STUDIES IN NORWAY 1965

by

MARKVARD A. SELLEVOLL

ABSTRACT

Part II reports results obtained from three widely separated seismic refraction profiles in Norway and a travel time study for seismic waves in Fennoscandia. The P_n velocities found are very close to 8.2 km/sec. Indications of a phase with velocity of 7.5 km/sec are observed. A phase with a velocity of about 6.6km/sec is well defined in the seismograms. The amplitude for this phase varies strongly. The velocity for the first direct longitudinal wave varies mostly from 6.00 km/sec to 6.15 km/sec. A crustal thickness from 31 to 38 km has been determined.

FOREWORD

The work on the data has mostly been carried out at Lamont Geological Observatory under the grant AFOSR 887-65 from the Air Force Office of Scientific Research as a part of the VELA- UNIFORM program of the Advanced Research Projects Agency.

I wish to express my sincere thanks to the following persons: Professor J. Oliver for making it possible for me to work a year at Lamont Geological Observatory of Columbia University. My stay was very interesting, instructive and stimulating. Dr. P. Pomeroy for this help and many suggestions during my work at Lamont Geological Observatory. Dr. L. C. Parkiser and Dr. J. Healy, the former and the present chief of the Branch of Crustal Studies, US Geological Survey, Menlo Park, for their interest and helpful cooperation in

the planning and accomplishing of the common research program.
The field team from the Branch of Crustal Studies, consisting of Mr. W. H. Jackson (leader), Dr. D. B. Hoover, Mr. J. Van Schack, Mr. D. J. Stuart and Mr. R. E. Warrick did an excellent work during the field measurements in Norway.
Mr. Kendrick and Mr. Mansfield of the American Embassy in Oslo assisted in the many arrangements during the field operation.
The very important and excellent assistance from the Norwegian Army, the Norwegian Air Force, and especially the Norwegian Navy under leadership of commodore Sigurd Valvatne, is greatly acknowledged.
The author is also indepted to the staff and students at the Seismological Observatory, Bergen University. They gave extremely valuable assistance during the planning, field operation and accomplishing of the research program.
The work described in Appndix C has been done together with Mr. R. E. Warrick, whose cooperation is greatly appreciated.

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INTRODUCTION

During the meeting of the International upper Mantle Committee held in Moscow, 11 - 14 May 1964, the following resolution was made:

" Considering the complexity of the geological structure of Europe and the importance of detailed comparative studies of the crust and upper mantle in this region for the UMP, and acknowledging the work already done in the Alps by the European Seismological Commission as an example of effective cooperation, the Upper Mantle Committee asks the European Seismological Commission to investigate the possibility of carrying out international profile researches of the crust and upper mantle on the territory from the northern coast of Scandinavia to the southern coasts of the Mediterranean, and to the west towards the Atlantic Ocean ".

In order to participate in this investigation, according to the resolution from the International Upper Mantle Committee, the Seismological Observatory, Bergen University, developed a plan during the autumn of 1964 to undertake a study of the crust and upper mantle along two east-west profiles across Southern Norway.

A support from ARPA made it possible for Dr. L.C. Parkiser, chief of Branch of Crustal Studies, US Geological Survey, Denver (now: Menlo Park) to propose a cooperative seismic measurement program in Norway for 1965 between Branch of Crustal Studies and Seismological Observatory. By this proposal the original plans could be considerably extended.

A planning conference was held in Bergen, April 1965, and the result of this conference was a plan for

A) a study of the upper mantle velocity and wave attenuation on a long north-south profile through Norway from Kristiansand to Tromsø,

B) a crust and upper mantle study along three shorter profiles:

1. Lofoten-Vesterålen
2. Flora-Åsnes
3. Fedje-Grimstad.

The field measurements were carried out in the period from 14 August to 4 September 1965.

The study of the data which was collected during the measurements along the north-south profile from Kristiansand to Tromsø was undertaken by Mr. R. E. Warrick at Branch of Crustal Studies, US Geological Survey, Menlo Park. A special technical report giving the result of this study is under preparation.

The present report includes three papers called Appendix A, B, and C. These three appendices show the present stage of the publications, which are the results from this research program.

Appendix A gives a technical description of the field measurement and the preliminary results concerning the profiles Flora-Åsnes and Fedje-Grimstad.

Appendix B gives the results from the measurements in the Lofoten-Vesterålen region.

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APPENDIX A

SEISMIC MEASUREMENTS IN NORWAY 1965

Flora - Åsnes and Fedje-Grimstad Profiles

(Preliminary report)

by

MARKVARD A. SELLEVOLL[1] and Richard E. WARRICK[2]

ABSTRACT

Two reversed seismic-refraction profiles were recorded between Flora-Åsnes and Fedje-Grimstad, Southern Norway, during the period 28 August – 4 September, 1965.

Depths to Mohorovičić discontinuity were determined to be approximately 36 km at Flora and Åsnes, 32 km at Bergen, and 35 km at Grimstad.

The velocity of the compressional wave in the mantle immediately below the Mohorovičić discontinuity was determined to be 8.25km/sec. There seems to be evidence for a phase with the appearant velocity of 7.5 km/sec. Other velocities determined in the crust are approximately 6.1 km/sec for the surface layer and 6.5 km/sec for the layer immediately below the surface layer.

Within the geological region, called the Bergen Arc System, the velocity 6.5 km/sec is obs[illegible] the surface. No characteristic surface layer velocity (6.1 km/sec) is observed in this region (the Fedje shotpoint).

INTRODUCTION

A program of cooperative seismic measurements in Norway for 1965 was proposed in February, 1965, in a letter from L.C. Pakiser of the U.S. Geological Survey to the University of Bergen. An agreement was soon reached between the Seismological Observatory, University of Bergen, and the Branch of Crustal Studies, U.S. Geological Survey, on a program for crustal studies and wave correlation in Norway.

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[2] Branch of Crustal Studies, U.S. Geological Survey, Menlo Park, Cal. U.S.A.

A planning conference was held in Bergen on April 5 through 8, 1965, between Professor Kvale, Associate Professor Sellevoll of the University of Bergen and Dr. Healy of the U.S. Geological Survey. The result of this conference was a preliminary plan for the study of crustal structure along the Lofoten-Vesterålen, Flora-Åsnes and Fedje-Grimstad profiles and an upper mantle velocity and wave attenuation study on a long north-south profile (see Fig. II-A. 1). The initial plans called for the Branch of Crustal Studies to furnish two array recording systems and two explosion firing and timing units. This participation was subsequently increased to four array systems and eight single-channel recorders in addition to the shot timing units. The Seismological Observatory provided eight portable three-component seismographs in addition to their permanent observatories.

FIELD OPERATIONS

The field operations were conducted in Southern Norway between 28 August and 4 September, 1965. Twelwe explosions were made to provide three at each end of each profile. Explosion times, positions, depth and size of the charges are included in Table 1. The explosions, numbered 1 through 7 inclusive, were utilized in the Lofoten-Vesterålen region study and in the long north-south profile reports which are in process.

All but three of the explosions were in coastal waters where they were assembled, inplaced, and fired from ships of the Norwegian Navy. The three inland explosions were inplaced, fired, and timed by the Norwegian Army Corp of Engineers in a swampy area near Åsnes.

The water shots were made up of 50-pound canisters of Nitromon WWEL which were assembled inside a structural steel framework to keep the charge intact during the inplacement operation. The assembled charge was primed, then lowered over the side of the ship. Care was taken to avoid fouling the firing lines during the time the charge was lowered to the bottom and while the ship withdrew to a safe distance. The average distance from explosion point to ship for the 1820-kg charges was 700 meters. The range of offset distances was from 385 to 1490 meters. No damage was reported on board the ship for any of the shots.

The explosives were detonated by use of a firing relay which was actuated by an electronic chronometer. The chronometer was synchronized with radio time signals from standard time stations. High voltage direct current was applied to the electric blasting caps to reduce the firing lag to millisecond values (Blasters Handbook, 1966).

The shotpoint instrumentation consisted of an electronic chronometer, a standard frequency radio receiver, a step-up transformer and rectifier, shot control and safety switches, and a photographic

oscillograph. The oscillograph recorded the chronometer impulses, the firing current signal, and the direct seismic arrivals at the ship. The oscillograph included a precision timing line generator to aid in timing the events (Fig. II-A. 2).

The explosions were located by triangulation, using coastal navigational charts of a 1 to 50,000 scale, and by sightings of buoys and shore reference points.

The series of explosions near Åsnes used T.N.T. as the explosive. The charges were placed in position on the bottom of a shallow water covered area by use of a raft. The charge depth was determined after the charge had reached equilibrium on the bottom. The depth to bedrock was estimated to be no more than a few meters below the charges. The explosives were detonated electrically. The shot instant, radio time signals, and chronometer pulses were recorded on an oscillograph. The 600 kg size limit for the largest shot was determined by the proximity to occupied structures and a desire not to cause physical damage to them.

RECORDING STATIONS

Three types of portable seismic recording systems were used : truck-mounted arrays, single - channel magnetic tape systems and three - channel oscillograph recording systems.

Array stations

Four truck-mounted array systems furnished and operated by the U.S. Geological Survey were used in this program. These seismic recording systems consisted of eight channels of signal conditioning with simultaneous recording on photographic paper and magnetic tape. These systems have been described previously (Warrick et al. 1961). Modifications since then have included the provision for recording all eight channels on magnetic tape and the inclusion of electronic compensation channels. These additional channels on the magnetic tape were achieved by eliminating of dual-level recording. The low frequency radio receivers were removed when their use was found not to be essential for timing. The signal path diagram (Fig. II-A. 3) oulines one of the eight identical signal channels. In this work the high frequency filter cut-off varied from 18 to 37 Hz depending upon the strength of local noise sources. EV-17 seismometers with a 1.0 Hz natural frequency were used. The low frequency amplifier cut-off occurred in the vicinity of 0.5 Hz. Six vertical seismometers were positioned along a line at 500-meter intervals and were connected to the recording system located at the center of the array through use of a tapered cable made up of small two-conductor copperweld cables. Two horizontal seismometers were

orientated so as to make an orthogonal set at one of the vertical seismometer positions near the recording system. The amplified seismometer signals were displayed at two levels with approximately 15 db separation by means of a photographic oscillograph and simultaneously recorded on magnetic tape (Fig. II-A-3a).

Three-component units

The Seismological Observatory operated eight three-component systems for this program. These systems were constructed by Mr. Fridtjov Veim, Seismological Observatory. The signal path diagram, (Fig. II-A. 4) provides an outline of the system. A tri-axial seismometer set composed of three Hall-Sears HS-1 detectors with a 4.5Hz resonant frequency determined the low frequency cut-off of the system. The amplifier high cut frequency was on the order of several hundred Hz, well above the seismic signal range. The internal crystal chronometer provided time marks at one-and ten-second intervals which were superimposed with the radio time signals into one channel of the oscillograph. A four-channel photographic oscillograph of the type used in electrocardiography provided the recording device (Fig. II-A. 4a).

Single-channel magnetic tape system

The Geological Survey provided. eight single-channel magnetic tape recording systems. These were prototype units designed by D. B. Hoover of the Branch of Crustal Studies. The systems used in this program are outlined in Fig. II-A. 5. A single vertical motion sensitive EV-17 seismometer of 1.0 Hz natural frequency was used as the detector. An attempt was made to put radio time on the tape before and after the shots were recorded. The output of the amplifier was recorded at two levels with a nominal separation of 30 db between levels.(Fig. II-A. 5a). These systems required two twelve-volt storage batteries for power and could record for several days continuously on one battery charge. In this work the systems were recording from 2 to 12 hours at a time, then they were moved and set up at a new location. Current versions of these recording systems have a continuous radio time channel using the WWVB transmission on 60 khz which yields an usable signal strength over most of North America.

RECORDING DIFFICULTIES

Aside from the common logistic problems the principle factors

contributing to a reduction in seismogram quality were timing problems and power frequency pickup. Radio time signals were of highly variable quality. At most locations some form of radio time signal could be identified aurally but often the signal quality was too poor for satisfactory recording. It was discovered later that the single channel magnetic tape systems required a good radio signal strength to make usable timing recording. Time signals from WWV, Washington; OMA, Prague; RWM-RES, Moscow, and DIZ, Potsdam were used at various times during this program (Ref.2). In Southern Norway the Potsdam signal seemed most consistent.

The power frequencies of $16\frac{2}{3}$ Hz from the electrified railings and to a lesser extend the 50 Hz from general use power appeared on the recordings, despite efforts to locate recording stations remote from these power sources. The amount of power frequency pick up increased whenever the cables and seismometers were exposed to wet weather.

ACCURACY OF DATA

Location: Recording locations were plotted on the best available topographic maps, nearly all on the scale of 1 : 100.000, of the "Gradteig" map series published by The Geographical Survey of Norway. Positions are estimated to be correct within ± 200 m. In some areas only the older "Amts" maps were available. These are of variable quality. The precision of location in the few places where older maps were used is expected to be less exact but difficult to estimate meaningfully.

The offshore explosion point locations were plotted on navigational charts, having a 1 : 50.000 scale, by visual sightings of reference points and a check of fathometer recordings. The location accuracy is estimated to be within ± 150 m at the shot location most distant from sighting points (Grimstad). The other locations are expected to have less location error. At Åsnes the explosion site was located by the use of a 1 : 100.000 "Gradteig" map with location precision estimated within ± 50 m.

TIMING CONSIDERATIONS

The quality of record timing varied considerably as a result of the difficulty in obtaining good radio time signals. The listing of recording positions Tables 2 and 3 includes a timing grade indication. Grades 1 and 2 could be timed accurately as either radio time was recorded on that recording or the chronometer phase was determined on a separate recording. Grade 1 recordings had both radio minute and second indications. Grade 2 had clear radio second indications. Grade 3 were recordings obtained with only the

chronometer. The timing accuracy of recordings in this grading was variable, as some of the chronometers had less stability than others and the time interval to the nearest radio check varied. Grade 4 recordings were used only for phase correlation, as they had no usable timing. Stations of this grade are indicated with a distinct symbol on the travel time plots to indicate these which were not used in the determination of the first arrival velocities.

The recording paper speed and the sharpness of energy onset allows an estimated average reading accuracy of ± ms. The sharpness of energy onset is the greatest variable in the consideration of timing accuracy of recordings of grades 1 and 2. The onset of the later arrivals are estimated to be read within ± 100 ms.

The apparent velocities and intercept times were obtained by the method of least squares.

INTERPRETATION OF TRAVEL TIME DATA

Fedje-Grimstad profile:

The first observable energy from the Fedje shot point, assumed to be P_g, (phase notations, see Appendix B) fits extremely well to a straight line with a velocity of 6.5 km/sec (Fig. II-A 6) and an intercept time of 0.2 sec. The small intercept time indicates that the high velocity is reached very close to the surface. The 6.5 velocity is higher than usual in Norway, but can probably be explained as an effect of the geologic conditions existing in the Bergen Arc System. The 6.5 velocity energy could be followed to an offset of about 70 km from the shot. As the 70km offset distance was approached a marked decrease in amplitude occurs so that the phase could not be traced beyond 95km.

This first strong secondary arrival appears to have the same velocity as P_g but with a delay of approximately 0.5 sec. This phase is assumed to be the first arriving energy from offset of 100 to 180 km where the P_n crossover occurs. This phase can be followed to beyond 300 km with varying amplitude, but is often the strongest amplitude within the P wave group.

P_n appears as a clear first arrival beyond the crossover from 180 km outward. The onsets are usually distinct. The best fit for a straight line for the P_n velocity is 8.25 km/sec.

There are indications of a phase between the P_n and P_b from approximately 200 to 300 km. This phase did not appear as a first arrival and varied in distinctness. The apparent velocity of this phase is approximately 7.5 km/sec.

The Grimstad end of the profile shows the usual velocity for the P_g of 6.0 km/sec., much less than the 6.5 recorded at the other end of the profile within the Bergen Arc System.

The travel time data obtained for the Fedje-Grimstad profile are presented in tables 2 and 3 and these values are plotted as two time-

distance curves in Fig. II-A. 6. The time-distance curves shown in this travel time diagram are based on first and secondary longitudinal arrivals.

The model presented in Fig. II-A. 7 fits the data well, but is given as a preliminary model for the Fedje-Grimstad profile.

Flora-Åsnes profile:

The P_g arrival from the Flora, as well as the Åsnes shotpoint fit well to a straight line in the travel time diagram Fig. II-A. 8. The P_g velocity is calculated to be 6.1 km/sec in both directions.

The P_b onsets from the Flora shotpoint are very scattered around the regression line representing the velocity 6.5km/sec in the travel time diagram Fig. II-A. 9. The P_b velocity (6.5 km/sec) determined from the Åsnes shotpoint is based on only three observations in the distance range 190 km – 300 km.

The determination of the P_n phase velocity (8.20 km/sec) from the Åsnes shotpoint is uncertain. The best fit for the phase from the Flora shotpoint identified as P_n, is a straight line giving the velocity 8.25 km/sec, which is the same P_n velocity as has been observed in both directions from the Fedje-Grimstad shotpoints. This velocity observations from the Flora and Åsnes shotpoints indicate that there exists a relative horizontal Mohorovičić discontinuity along the Flora-Åsnes profile.

Fig. II-A. 9 shows a preliminary calculated crustal structure along the Flora-Åsnes profile, assuming that the crust consists of three layers with the constant velocities 6.1 km/sec, 6.5 km/sec and 8.25 km/sec and a horizontal Mohorovičić discontinuity.

A lot of refraction profiles have been investigated in Fennoscandia during the last 10 years. The result of these studies shows that the velocity range of 5.90 – 6.10 km/sec seems to be a relatively well established velocity for the upper crustal layer (just below the thin surface layer). The velocity range of 8.20 – 8.25 km/sec is also well established for the P_n phase. The phase P_b with the apparent velocities between 6.50 – 6.70 km/sec is also observed very often, but the scattering in the onsets and the amplitude variations of this phase indicate that it is not all the head-wave P_b, but may be a combination of an eventual head-wave, reflections from Mohorovicic discontinuity or eventual other phase combinations that are interpretated as P_b. This still needs a careful investigation to arrive at a satisfactory explanation.

The Seismological Observatory, Bergen, has recently acquired an instrument for handling magnetic tape data. We are hoping that by a continuation of the data handling process, which has been started, we shall be able to continue the work concerning the phase correlation and crustal models for the Flora-Åsnes and Fedje-Grimstad profiles.

ACKNOWLEDGEMENT

Norwegian Navy cooperation was arranged through negotiations between Professor Anders Kvale and Commodore Sigurd Valvatne. The Navy provided the ships and personnel necessary to assemble and to inplace all the explosions fired offshore.

We wish to express our appreciation to the officers and crew of the following ships of the Norwegian Navy:

KNM "Borgen" (Lieutenant commander Asmundsen)

KNM "Sauda" (" Pedersen)

KNM "Uller" (Captain Bruland)

KNM "SKN 3" (Lieutenant commander Grønnevik)

KNM "SKV 3" (Skipper Thommasen)

KNM "Horten" (Lieutenant Helleseth)

We also wish to express our best thanks to the following Navy-officers for help and assistance:

Captain M.A. Norberg, SKS.

Commander E.A. Bjørnsen, SKN

Commander B. Dahlen, TKBI.

Lieutenant commander Hansen, SKV

Lieutenant commander Martinsen, SKV

Lieutenant commander Moen, SKV

Lieutenant commander N. Kvamsdal, SKS

Lieutenant T. Gåsvær, SKV

The Norwegian Army handled the one land shot point (Åsnes) and provided special transportation. The cooperation of Lieutenant colonel Kolbu who was responsible for these operations is gratefully acknowledged. The US Air Force and the Norwegian Air Force provided special transportation for instruments and explosives.

Messrs. Kendrick and Mansfield of the American Embassy in Oslo assisted in the many arrangements necessary in such a field operation. Jakob Bleie of the Seismological Observatory assisted in the preparations and planning of the field operations and Mr. Olav Eidholm has given very valuable assistance in the preliminary data preparation. Wayne Jackson of the Branch of Crustal Studies was field supervisor of the American group. Fritjof Veim was supervisor of the Norwegian group.

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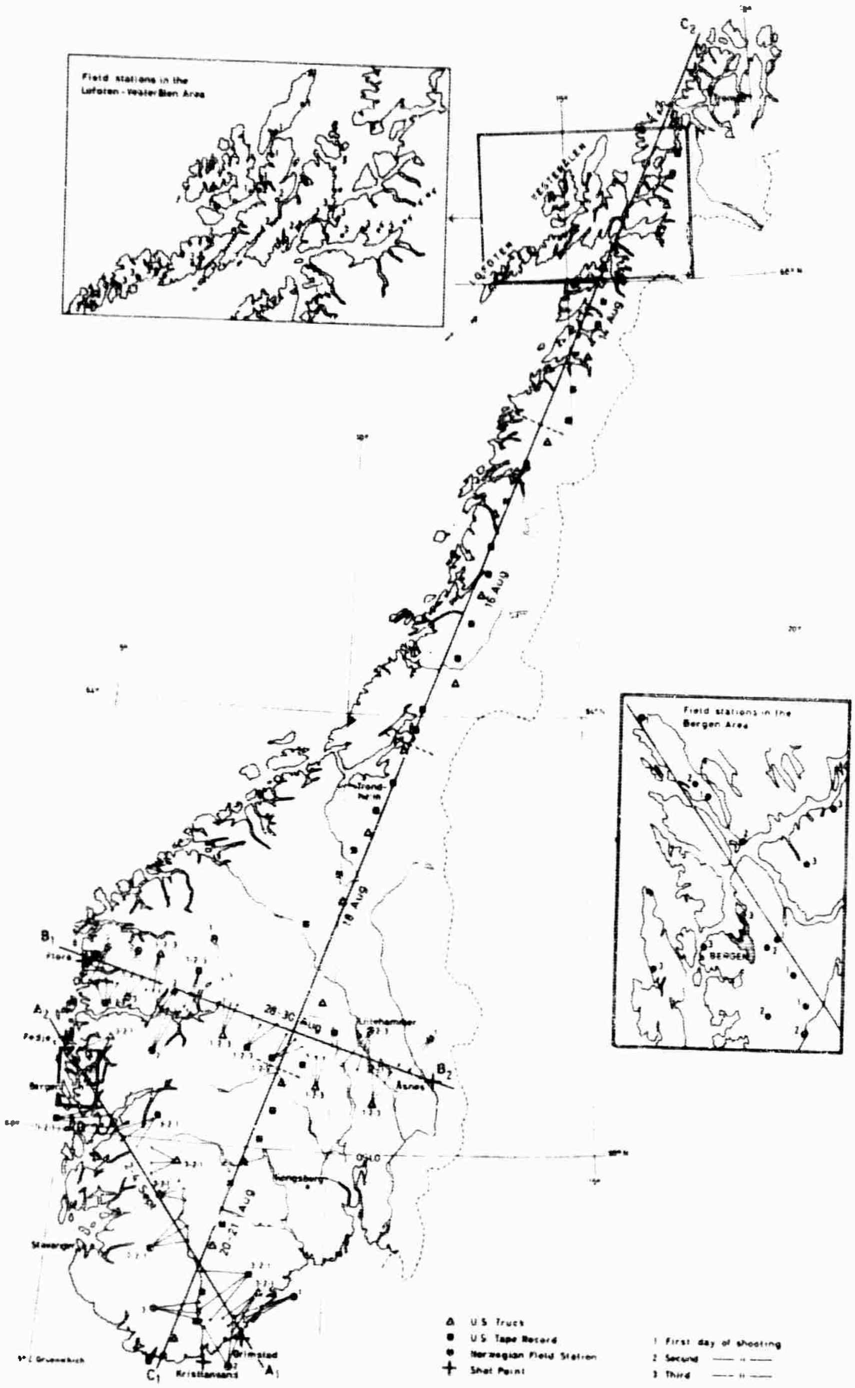

Fig. II-A. 1 : Seismic refraction measurements in Norway 1965.

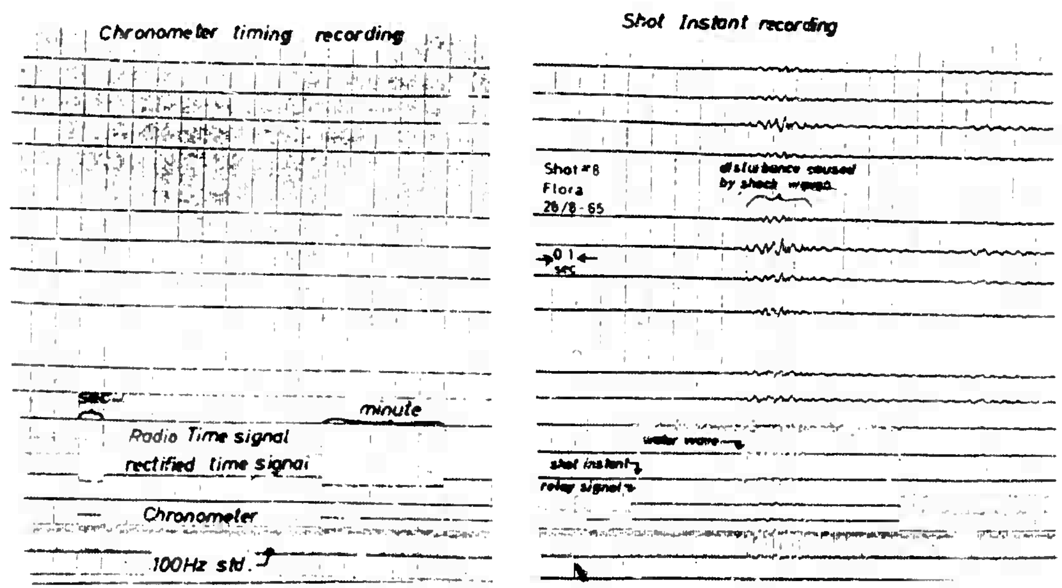

Fig. II-A. 2 : Recording of the shot moment.

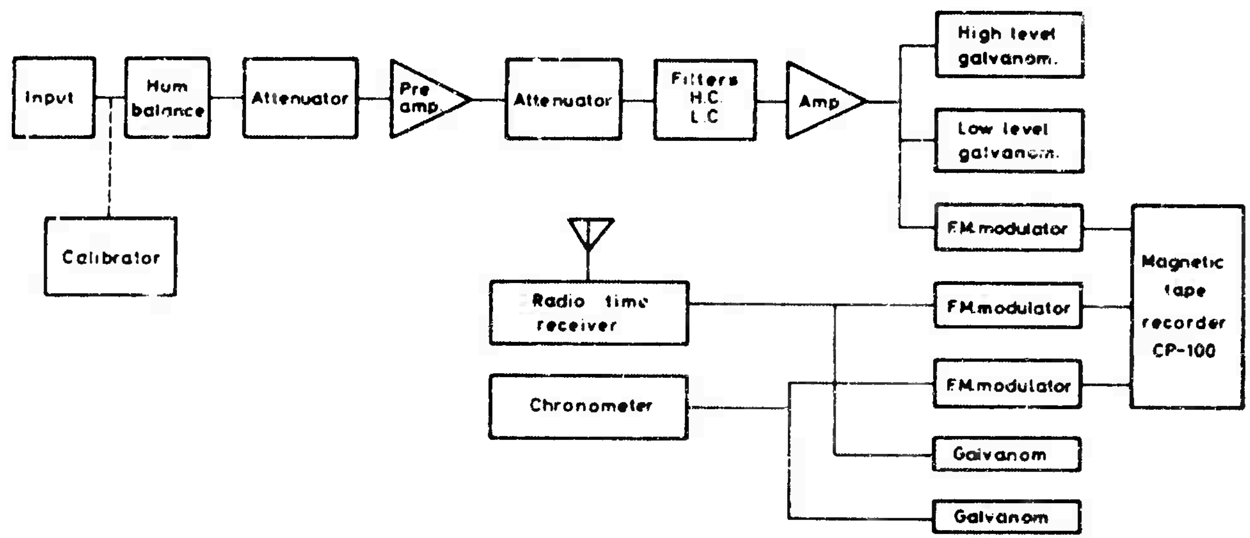

Fig. II-A. 3 : A block diagram showing the signal path (on one channel) and timing system: Array Unit.

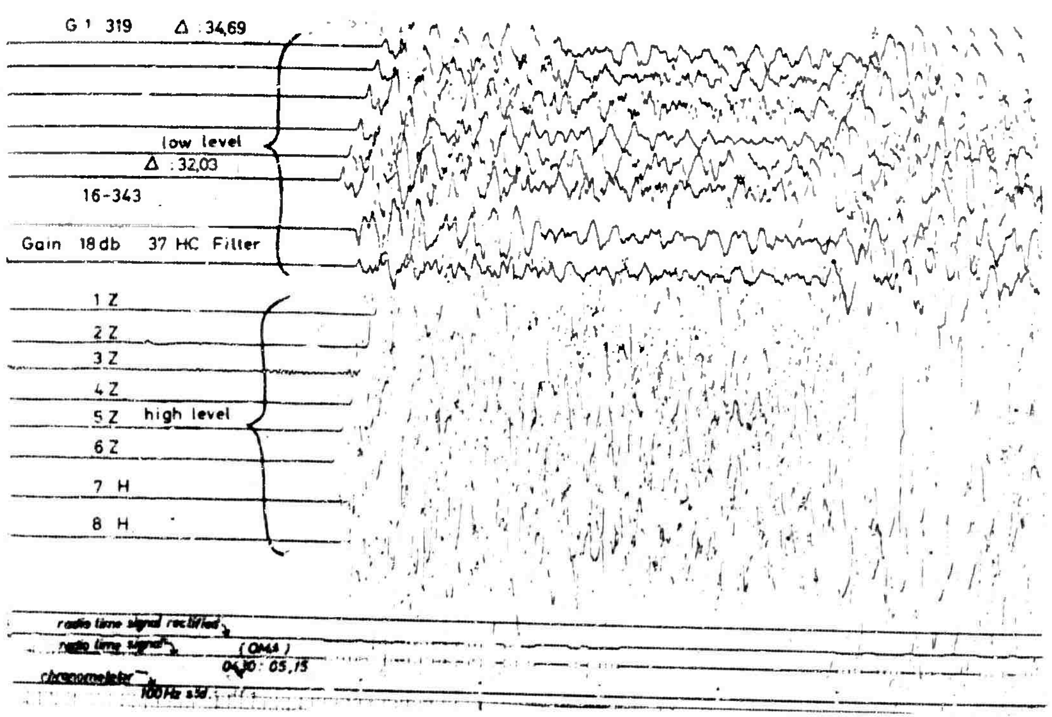

Fig. II-A, 3a: A typical seismogram recorded on one of the array units.

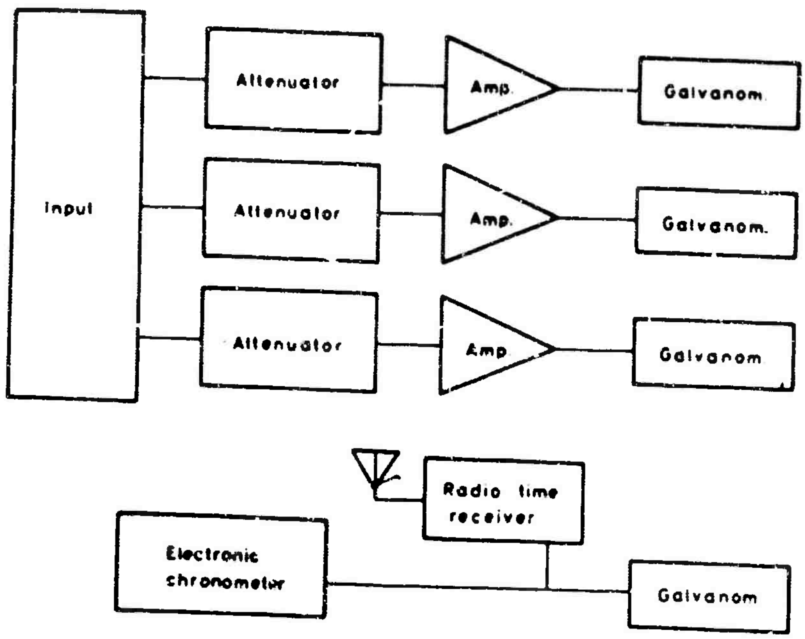

Fig. II-A. 4 : A block diagram showing the signal path and system: Three-component units.

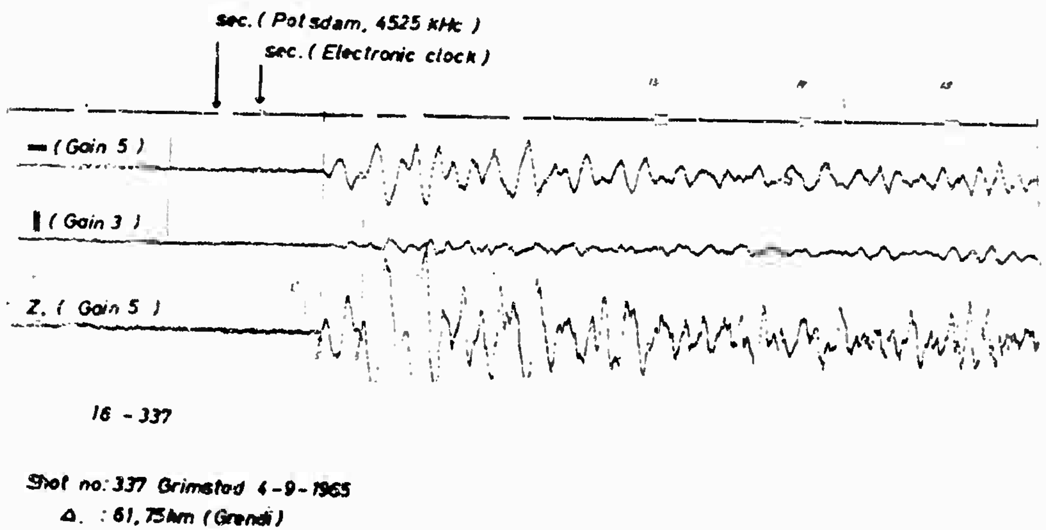

Fig. II-A. 4a: A typical seismogram recorded on one of the three-component units.

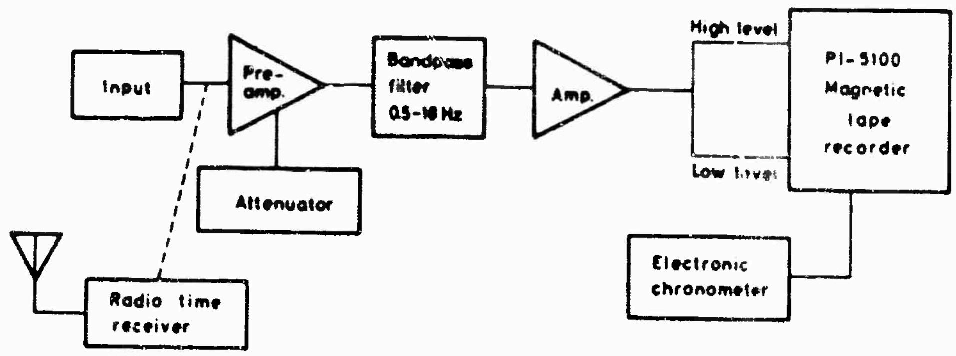

Fig. II-A. 5 : A block diagram showing the signal path and timing system: Single-channel magnetic tape units.

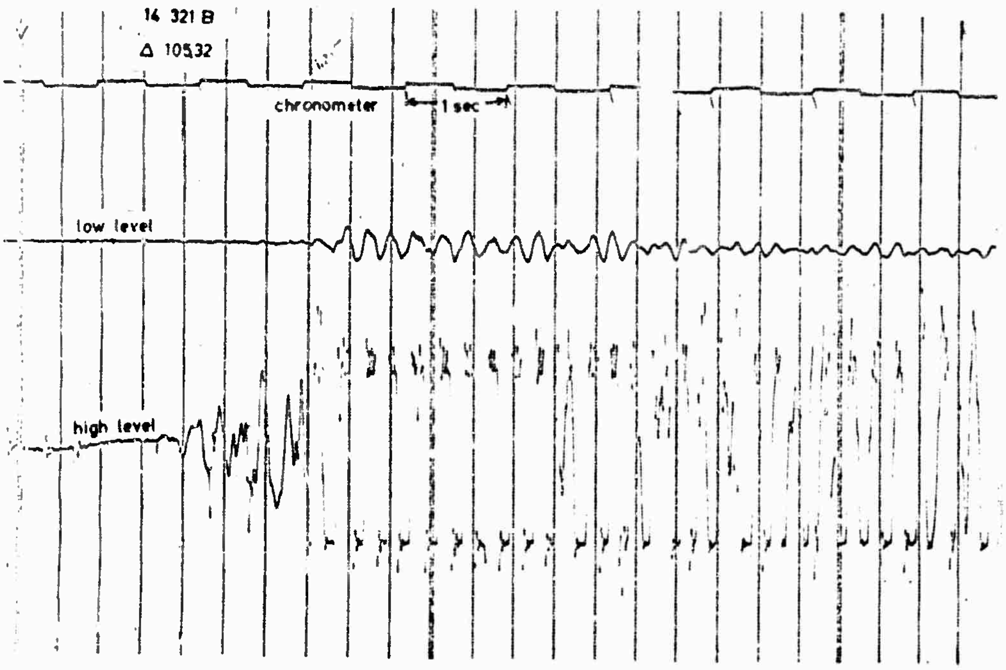

Fig. II-A. 5a: A typical seismogram recorded on one of the single-channel magnetic tape units.

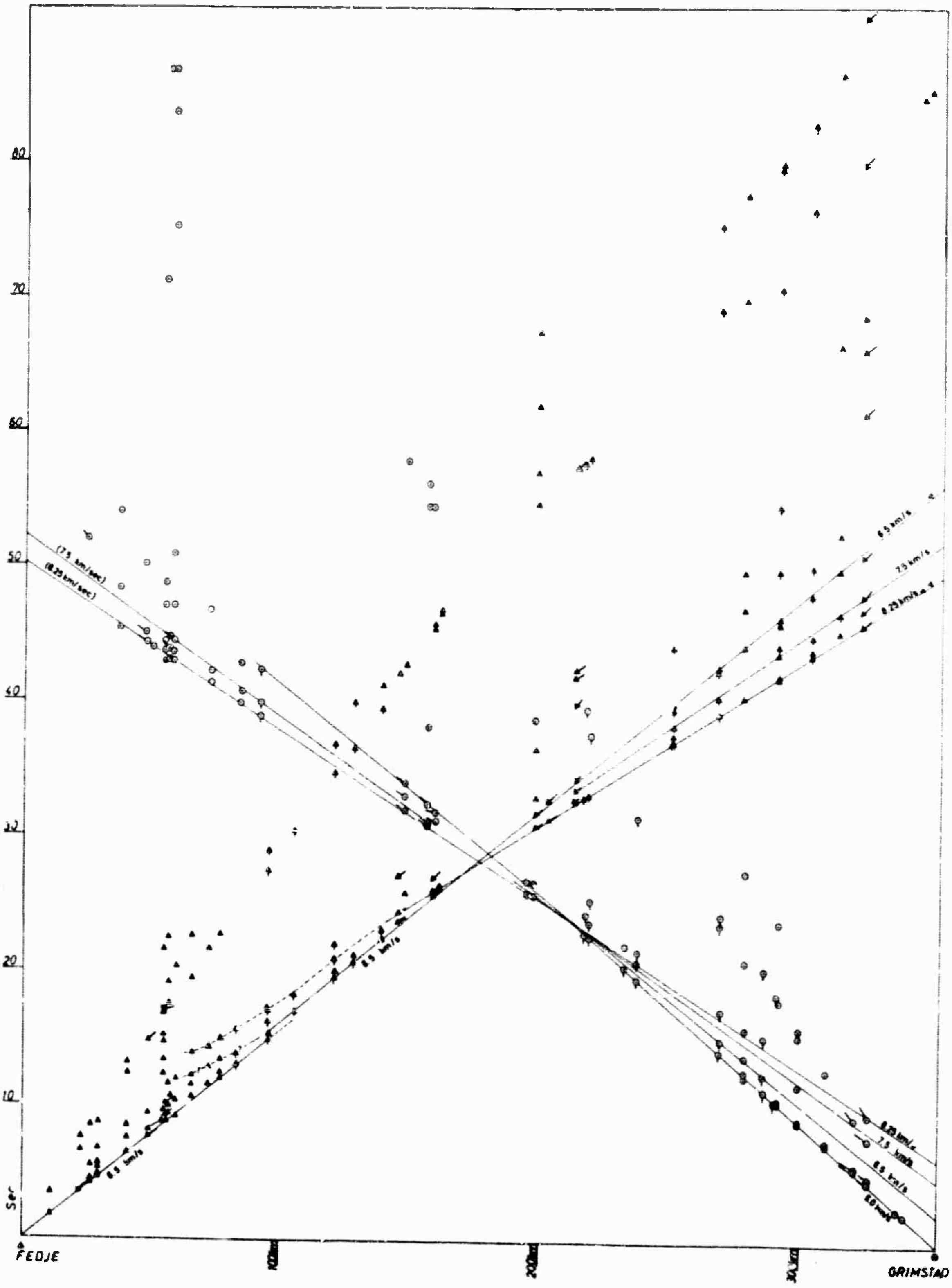

Fig. II-A. 6 : Travel-time curves for the Fedje-Grimstad profile.

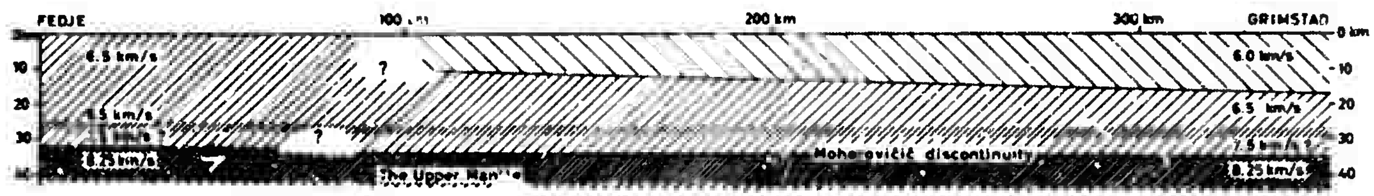

Fig. II-A. 7 : A preliminar crustal model for the Fedje-Grimstad profile.

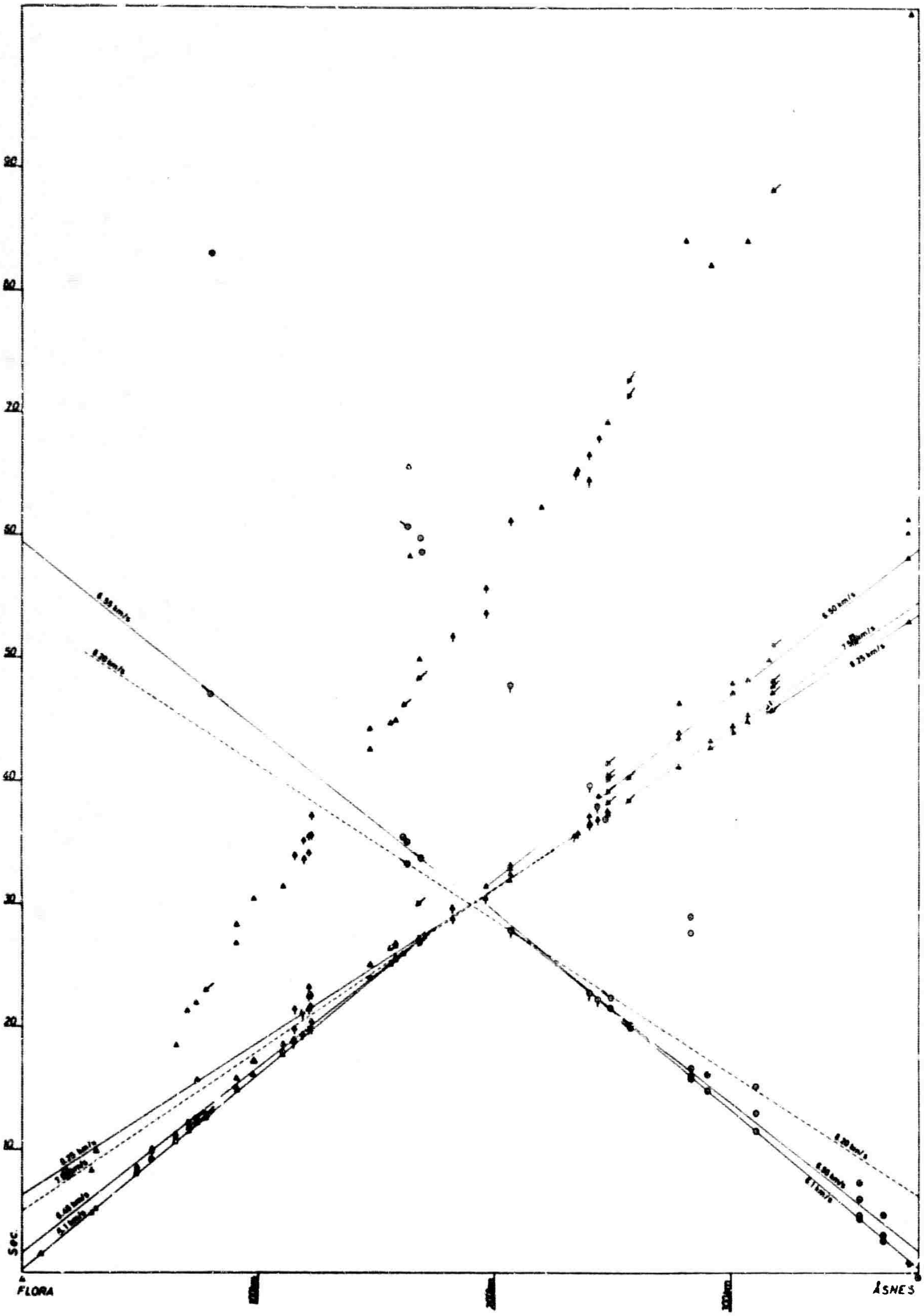

Fig. II-A. 8 : Travel-time curves for the Flora-Åsnes profile.

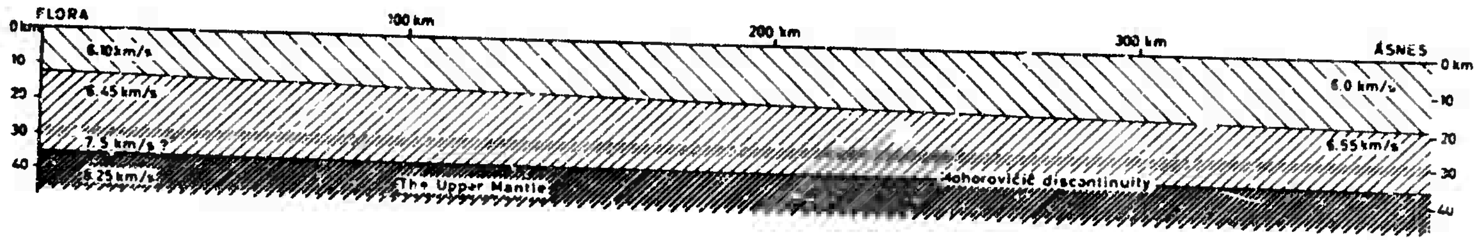

Fig. II-A. 9 : A preliminar crustal model for the Fedje-Grimstad profile.

APPENDIX A

TABLES

I–V

SHOT No.	STATION	DATE 1965	TIME (GMT)	POSITION North lat.	East long.	DEPTH (m)	SIZE (kg)
1	Tromsø	14/8	04 01:00.08	69°47.60'	18°34.30'	100	1000
2	Tromsø	16/8	04 01:00.33	69°47.60'	18°35.90'	117	6550
3	Tromsø	18/8	04 01:00.33	69°47.35'	18°36.00'	130	8100
4	Kristiansand	18/8	04 30:00..	58°03.25'	8°03.58'	56	2000
5	Tromsø	20/8	04 01:00.31	[illegible]°47.30'	18°35.90'	146	1950
6	Kristiansand	20/8	04 30:00.30	58°01.23'	8°04.18'	115	5000
7	Kristiansand	21/8	07 30:00.23	58°01.23'	8°04.38'	83	1360
8	Florø	26/8	05 01:00.00	61°30.05'	5°08.65'	65	1000
9	Åmot	28/8	05 30:00.36	60°39.00'	11°32.53'	2.5	150
10	Florø	29/8	04 01:00.18	61°30.90'	5°08.10'	85	1000
11	Åmot	29/8	04 31:00.35	60°39.00'	11°32.53'	3	320
12	Florø	30/8	04 03:00.07	61°30.90'	5°38.90'	80	1700
13	Åmot	30/8	04 29:59.58	60°39.00'	11°32.53'	5	600
14	Fedje	2/9	04 01:00.10	60°49.82'	4°49.40'	100	1005
15	Fedje	3/9	04 01:00.11	60°49.80'	4°49.53'	100	1000
16	Grimstad	3/9	04 30:00.38	58°17.30'	8°40.34'	75	1000
17	Grimstad	3/9	14 01:37.86	58°17.80'	8°34.80'	79	1000
18	Fedje	4/9	04 03:00.13	60°49.80'	4°49.53'	100	1000
19	Grimstad	4/9	04 40:00.34	58°18.83'	8°35.77'	69	1000

Table I. Shotpoint location and explosion size, depths and times.

SHOT No.	LOCATION No.	DISTANCE Δ (km)	TRAVEL TIME (sec.)	TIMING PHASE
18	346	13.00	2.71	1
16	345	15.47	2.81	1
19	343	26.82	4.64	
			6.96	
			7.80	
			9.59	
		29.90	4.97	
			5.89	
			8.75	
			10.41	
16	343	32.03	5.52	1
			5.71	
			9.35	
		34.09	5.03	
			6.00	
			10.00	
18	340	43.[illegible]	7.00	1
			7.58	
			12.00	
20	339	52.98	9.01	
			9.19	
			13.78	
			12.35	
			15.90	
20	337	61.57	10.40	1
			10.60	
			17.90	
			23.77	
20	335	74.20	12.36	2
			12.76	
			13.00	
			15.95	
			20.85	
			[illegible]	
19	320	155.40	25.04	2
			26.69	
			30.64	
		157.95	25.86	
			26.79	
17	307	193.20	30.15	
			30.85	2
			52.40	
		194.86	34.17	
			30.90	
18	306	196.46	30.97	1
			31.19	
			32.49	
			38.20	
			54.48	
			56.18	
		198.84	30.80	
			31.40	
			38.06	

SHOT No.	LOCATION No.	DISTANCE Δ (km)	TRAVEL TIME (sec.)	
19	325	2[illegible]5.05	31.94	
			33.04	
			34.01	
			37.89	
		286.93	32.00	
			33.19	
			34.86	
18	318	290.60	41.39	
			42.72	
			46.73	
			8[illegible].67	
17	312	294.93	43.76	
			43.69	
			44.68	
			47.01	
			50.91	
			75.87	
			83.98	
		295.09	43.71	
			44.91	
			47.31	
			51.18	
19	2	297.97	43.9	?
			86.8	
19	310-0	298.43	42.09	
			43.69	
			47.07	
			48.70	
17	8	298.59	33.41	
			81.15	
19	313	300.04	39.41	3
			40.36	
			48.77	
			48.08	
			50.13	
			86.12	
15	2	302.90	44.35	
			73.8	
			81.9	
19	313-1	303.41	43.95	?
16	308	305.57	44.30	8
		305.17	44.85	
			50.36	
		307.93	44.41	
			45.19	
18	309	318.18	65.38	3
			68.33	
			56.00	
19	300	318.76	47.09	8
			51.95	
			95.95	
		329.98	47.88	

Table II Grimsted Recordings

SHOT No.	STATION No.	DISTANCE Δ (km)	TRAVEL Time (sec)	TIMING Grade
14	301-8	11.16	1.79	3
			3.3[illegible]	
13	300	21.93	3.95	2
			6.43	
		23.57	5.98	
			7.75	
17	303-2	36.70	4.88	1
			4.41*	
			5.50	
			.49	
14	304-3	39.68	4.38	1
			4.85	
			5.36	
			5.68	
			6.77	
			8.76	
17	305-3	40.89	6.47	3
			7.77	
			8.48	
			12.38	
			13.80	
15	308	49.17	7.71	4
			8.70	
			9.42	
			14.90	
		51.6	7.94	
			8.46	
			15.29	
14	9	55.13	8.8	
			12.3	
			13.4	
			15.2	
			14.7	
15	8	55.13	9.4	
			14.[illegible]	
			17.0	
			21.4	
18		55.13	[illegible]	
			15.62	
14	312	55.46	8.81	
			9.32	
			10.14	
			16.98	
		57.83	9.84	
			10.33	
			10.71	
			17.22	
19	310-2	56.96	9.39	
			9.99	
			11.60	
			17.59	
			19.12	
			22.49	
18	314-1	55.15	9.2[illegible]	1
			10.35	
			11.92	
			12.34	
			20.33	
14	315-5	66.07	10.70	2
			11.60	
			12.26	
			13.93	
			19.49	
			22.63	
14	317	72.64	11.61	3
			12.90	
			14.60	
			21.62	
17	318-5	77.13	12.11	
			12.49	
			13.42	
			14.97	
			12.90	
			22.71	
18	325	146.60	23.72	2
			23.86	
			24.67	
			27.11	
			42.16	

SHOT No.	STATION No.	DISTANCE Δ (km)	TRAVEL Time (sec)	TIMING Grade
		148.25	24.81	
			24.30	
			24.69	
			25.83	
			27.93	
			42.42	
			45.73	
15	326	150.95	25.73	2
			26.00	
			26.96	
			45.46	
			45.79	
		161.00	26.00	
			26.23	
			27.13	
			45.42	
			46.03	
14	327	161.70	24.26	2
			26.60	
			25.62	
			46.88	
		161.81	26.24	
			26.43	
18	328	153.33	30.96	1
			31.82	
			32.99	
			36.67	
			54.79	
			57.13	
			42.09	
			47.54	
		199.33	30.96	
			31.77	
15	329	203.08	31.39	
			32.81	
			55.81	
		209.[illegible]	31.98	
			33.11	
14	330	213.9	32.78	4
			32.96	
			[illegible]	
			34.93	
			60.09	
		214.34	32.44	
			32.83	
			33.96	
			34.36	
			39.86	
			41.93	
			42.45	
			57.04	
			57.64	
15	343	322.86	45.09	1
			47.08	
			48.08	
			51.07	
			61.62	
			66.32	
			68.92	
			80.22	
			91.06	
		325.63	46.15	
			47.54	
			43.34	
			51.35	
			61.91	
			66.42	
			69.22	
			80.64	
			91.57	

Table II. Fedjo Recordings

SHOT No.	STATION No.	DISTANCE Δ (km)	TRAVEL Time (sec)	TIMING Grade
11	301	4.09	6.73	1
			12.90	
11	302	14.91	8.60	2
			3.05	
			4.78	
11	403	94.98	4.37	•
			4.44	
			5.98	
			7.34	
13	4	63.09	11.3	
			15.2	
			80.8	
13	308	89.73	14.80	1
			16.12	
			25.87	
13	228	96.55	15.70	3
			15.98	
			18.63	
			27.76	
			29.04	
11	211	189.12	25.16	2
			34.45	
		183.6	80.40	

SHOT No.	STATION No.	DISTANCE Δ (km)	TRAVEL Time (sec)	TIMING Grade
9	712	130.51	21.70	1
		132.30	21.62	
			34.97	
			39.98	
			40.15	
13	211	189.12	19.96	1
			34.95	
		183.80	20.39	
			34.65	
			35.07	
11	259	210.90	33.79	1
			58.82	
		212.71	11.09	
			59.09	
11	280	216.71	13.90	1
			35.10	
			60.01	
		218.94	35.35	
			35.77	
			35.48	
			61.04	
13	230	300.19	47.09	1
		or	47.18	
			60.97	
		302.05	47.02	

Table IV. Åreas Recordings

SHOT No.	STATIONS No.	DISTANCE Δ (km)	TRAVEL Time (sec)	TIMING Grade
[illegible]	241	8.22	1.44	3
12	B-235	48.45	7.94	3
			8.07	
			8.39	
10	234	54.97	9.13	3
			9.25	
			9.81	
			10.26	
10	233	65.21	1[illegible].60	
			10.91	
			11.22	
			18.48	
8	232	70.37	11.43	1
			11.74	
			12.23	
			21.34	
		72.16	11.80	
			12.62	
			12.38	
10	231	74.06	12.16	1
			12.47	
			15.74	
			21.99	
		76.86	12.49	
			12.77	
12	230	77.87	12.54	1
			12.74	
			17.07	
			23.05	
		79.74	12.87	
			13.06	
			13.18	
			23.37	
10	229	91.60	14.88	3
			15.08	
			15.83	
			26.86	
			28.36	
6	228	98.20	14.15	3
			17.96	
			30.49	
10	227	110.39	17.86	1
			18.04	
			18.61	
			31.48	
8	223	147.75	24.07	3
			25.06	
			27.45	
			42.68	
			44.32	
8	221	1[illegible].12	25.11	1
			30.45	
			44.80	
		157.78	73.41	
			26.48	
8	222	158.08	25.55	1
			25.43	
			26.65	
			26.87	
			44.96	
10	220	141.46	25.98	2
			44.25	
		153.87	46.30	
			46.47	
			58.49	
			45.[illegible]	
12	219	168.06	26.81	1
			27.32	
			30.09	
			48.46	
			49.98	
		170.68	27.14	
			27.71	
			30.22	
			48.55	

SHOT No.	STATIONS No.	DISTANCE Δ (km)	TRAVEL Time (sec)	TIMING Grade
8	212	248.33	37.40	1
			37.47	
			38.11	
			39.28	
			40.23	
			40.59	
			41.56	
			63.46	
		250.86	37.90	
			37.74	
			38.46	
			39.34	
			40.49	
			40.85	
			41.85	
			69.60	
10	211	256.97	38.40	2
			40.39	
			43.96	
			71.59	
			72.84	
		258.60	38.72	
			40.61	
			64.22	
			72.05	
			73.29	
12	207	278.[illegible]	41.25	1
			44.25	
			46.48	
			(84.30)	
10	209	292.13	42.88	1
			43.44	
			44.62	
			46.20	
			82.32	
10	208	301.42	44.14	1
			44.65	
			49.14	
10	207	307.57	45.01	1
			45.67	
			51.30	
9	206	318.74	47.05	2
			48.59	
			49.14	
			49.57	
			52.49	
			89.78	
		319.94	46.87	
			48.38	
			48.52	
			49.34	
			52.22	
			49.47	
6	202	345.[illegible]	51.09	1
			57.05	
8	201	375.90	53.29	1
			58.47	
			60.59	
			61.64	
			103.54	

Table V Flora Recordings

APPENDIX B

SEISMIC MEASUREMENTS IN NORWAY 1965
LOFOTEN - VESTERÅLEN REGION

by

MARKVARD A. SELLEVOLL[1]

ABSTRACT

The Lofoten-Vesterålen district in Northern Norway belongs to a region with very high gravity anomalies (+ 138 milligal in the Lofoten area). A seismic refraction study carried out in this region indicates that this gravity hight, is caused, at least partially, by a thinning of the upper crustal layer.

INTRODUCTION

The Lofoten-Vesterålen region of Northern Norway was the subject of special study during the cooperative program of seismic measurements conducted in Norway the summer 1965 by the Seismological Observatory, Bergen University, and U.S. Geological Survey Branch of Crustal Studies. This paper deals with the results obtained during the measurements in the Lofoten-Vesterålen region. The upper left part of Fig. II-B. 1 shows the explosion points and profile lines of the program.

The study of the Lofoten-Vesterålen region was made by the eight Norwegian recording units with the four explosions from Tromsø. (Sellevoll and Warrick 1967.) The location of the recording stations and the explosion point are also shown in Fig. II-B. 1, which is an enlargement of the area within the frame in the figure. All the planned recording stations are indicated. The stations used in this study are indicated by big filled circles. These stations are concentrated around a line from the explosion point along the Lofoten-Vesterålen region.

[1]Lamont Geological Observatory of Columbia University. On leave from the Seismological Observatory, Bergen, Norway.

The main reason for the concentration of the Norwegian field stations in the Lofoten-Vesterålen region were the geological features of this region and the interesting results of a gravity survey carried out by The Geographical Survey of Norway[1] (NGO). NGO has presented a map showing the Bouguer anomalies in Northern Norway. This map shows that the Lofoten-Vesterålen region belongs to a region with extremely high positive Bouguer anomalies Fig.II-B.2.

No counter-shot was fired in the southern Lofoten area because of time limitations. Therefore, the results obtained have been based upon some assumptions, but the results gained are very interesting and encouraging.

THE GEOLOGY

The general setting of the geology in the region of this study is shown on the geological map of Norway by Holtedahl and Dons (1960). A part of this map is shown in Fig. II-B. 3.

The rocks in the Lofoten and Vesterålen groups are mainly gabbro, norite, and anorthosite. In connection with the gabbros occur ultrabasaltic segregations, including titaniferous iron ores. The Lofoten rocks were formerly considered to form a petrographic province of their own and have also been considered to be of Caledonian age. This rock group has been called „ The plutonic rocks of Lofoten ".

K. Heier (1960) has published a paper on the geology in the Vesterålen district, especially the island Langøy has been studied. His work shows that „ The plutonic rocks of Lofoten " constitute a series of high regionally metamorphosed rocks into which some igneous rocks are intruded. Heier considers the rocks in the Vesterålen district to form a continuation to the west of the rocks of the basal complex. The distinction being a change from amphibolite to granulite mineral facies from the east to the west.

According to Heier the question of the ages of the Lofoten-Vesterålen rocks are still undecided. Molybdenite from this district gives ages about 2.10^9 years by Re/Os method. Heier's comment to this finding is that this may be „ a relict age " of pre-Cambrian rocks now intermixed in the Caledonian gneisses.

Heier (1960) has on the basis of his observations, especially on Langøy, found it possible to fit his data into the following chronological sequences of events.

1. Deposit of Caledonian sediments upon a „ basement " of pre-Cambrian rock ($2{,}3 \times 10^9$ years old) and local igneous activity.
2. Early Caledonian orogence activity with regional metamorphism of both the sediments and the basement rock.

---

[1] Norges Geografiske Oppmåling (NGO)

3. Formation of paleogenic granite magmas and local migration of these magmas to form masses such as the younger granites.
4. After this metamorphism, intrusion of gabbros, monzonite and anorthozite.
5. Intrusion of gabbro with retrograde metamorphism.
6. Regional thrusting of rocks from the west towards the east.

FIELD MEASUREMENTS

The shotpoint west of Tromsø was selected on the basis of geology, water depth, and fishing considerations. This shot point was marked by a buoy and the position was determined by triangulation with known positions.

Table 1 gives the date, explosion time, coordinates, water depth, and charge sizes of the four explosions. Details relating to the field techniques have been described by Sellevoll and Warrick (1967).

Shot No.	Date	Explosion time (GMT)	Coordinates	Water depth	Charge (kg)
1	14. Aug. 65	04h 01m 00,02s	69°47.40' N 18° 16.10' E	108 m	1820
2	16. Aug. 65	04h 01m 00,33s	— " —	117 m	455[illegible]
3	18. Aug. 65	04h 01m 00,33s	— " —	120 m	9100
4	20. Aug. 65	04h 01m 00,33s	— " —	108 m	7950

Table 1: Data on the explosions.

TERMINOLOGY AND SEISMOGRAM READING

Various proposals have been made in recent years to revise or replace the traditional terminology for seismic waves in the uppermost part of the Earth. In this paper the terms P_g, P_b and P_n will be used as defined by Sellevoll (1967).

All field stations were placed on crystalline rocks. The exact geologic situation at the shotpoints is not known, but it is highly possible that the crystalline sea-bottom is covered by less than 50 meters of recent sediments.

The most important step in reading the seismograms is the identification of significant wave arrivals. At greater distances, or in the presence of high noise, identification is far more difficult. With

a single channel, we must rely on changes in amplitudes or character to identify the signal. With three component seismometers Z, T and R it is often easier to identify arrivals.

In order to improve the identification possibilities of secondary arrivals the photographically recorded Z components have been transferred to a magnetic tape and played back through a filter system.

Fig. II-B.4 shows a block diagram illustrating the method used. The seismograms were placed on a rotating drum, and the selected trace on the seismogram was followed through a movable sight. The movements of the sight were transferred to a potentiometer which produced a variable voltage. This signal was then transferred to a modulator, and an FM signal was recorded on the magnetic tape, using a Honeywell LAR 7400 recorder. The recording speed was 3/8 ips and the playback speed was 17/8 ips. The filtering was made with Krohn-Hite 330 AR–4 filter and recorded on a four channel Sandborn recorder.

A minimum pass band width was used by setting the frequencies for low and high cut-off frequencies equal. This produces a narrow band pass characteristic with cut off slopes of 24 db per octave. The peak of the filter band pass was moved in steps of one Hz from 3 to 10 Hz.

Fig. II-B.5 shows an example of a filtering analysis of the Z-component recording at the station 412. The frequency variation in the different phases can be clearly observed. The frequency response for the recording instrument used is relatively flat above 4 Hz; consequently, the amplitudes can be directly correlated for all filter settings down to 4 Hz. Below 4 Hz the recording instrument cut off reduced amplitudes. Fig. II-B.5 shows that most of the energy is transmitted at frequencies lower than 4 cps.

By comparing the filtered seismograms in Fig. II-B.5 with the unfiltered Z component from station 412 in the seismogram montage Fig. II-B.6 (the arrows in Fig. II-B.6 correspond to the arrows in Fig. II-B.5) it is shown that the onset for the P_b, P_{x1} and P_{r} can be more easily determined on the processed seismograms than on the original seismograms. To identify some secondary arrivals we must depend on techniques that enchance the late-arriving energy compared to the trains of earlier waves that keep the seismometers in constant agitation.

The recording paper speed at the different recording units varied usually from about 33 to 38 mm/sec. In order to standardize the recording length per second and at the same time make a seismogram montage a computer program was written.

12 sec of the Z component recording on all seismograms have been digitized and the data have been processed in an IBM-1620 electronic computer. With the help of an IBM-162F plotter the seismograms have been plotted as a reduced travel time diagram. The technique used is illustrated in the upper portion of the flow diagram (Fig. II-B4). Fig. II-B.6 shows the seismogram montage for the Lofoten-Vesterålen experiment.

DATA ACCURACIES

On most of the seismograms the first break is clearly defined, and the beginning of the p' ase can be read to about ± 20 ms. The stations 402 and 403 hav doubtful timing and these two seismograms are, therefore, laced in the traveltime diagram where they fit best, according to t.e distances. The onset of secondary arrivals probably is not reliable to better than ±100 ms and is even more uncertain for the P_{x1} and P_{x2} phases.

PHASE CORRELATION AND TRAVEL TIME

In the analysis of the seismograms an attempt was made to read all the distinct pahses of the P group. The earliest arrivals plus late arrivals, which can be seen from the seis gram montage, are reliable in time and are coherent. Arrival tim of each phase at all stations were read, and the results are prese ed in table 2.

From Fig. II-B. 6 it can be seen t the onset for P_b and P_n fit relatively well to a straight line up to a distance of about 250km. For the most distance stations, 411 and 412, both P_n and P_b arrivals are much to early. As will be discussed later, these early arrivals are probably due to a thinning of the crustal layers which would explain the increase in the apparent velocity southward beyond about 260 km from the shot point. For this reason the stations 409, 410, 411 and 412 have been left out in the calculation of the least square fits for P_n and P_b.

Velocity measurements carried out on short profiles in the metamorphic rocks in Norway show that a velocity of approximately 6.1 km/sec is usually obtained as the first „direct wave" out to the crossover distance for later P arrivals (Sellevoll and Warrick 1967). If in the Fig. II-B. 6 a line is drawn through the zero point with a 6.1 km/sec velocity, the line will fit very well to the first onsets from stations 413 and 415. This indicates that the first direct wave correlates well with previous measurements, and the first onset in the seismograms from station 413 and 415 is therefore interpretated as P_g

When time is in seconds and distance is in kilometers, the travel time for P_b and P_n for the stations from 408 to 413 in table 2 can be represented by the following equations:

$$t_{Pg}\ 0-415: \left[(0) + \frac{\Delta}{6.00} \right] \text{sec}$$

$$t_{Pb}\ 0-408: \left[2.42 + \frac{\Delta}{6.66} \right] \text{sec}$$

$$t_{Pm}\ 0-408: \left[6.39 + \frac{\Delta}{8.26} \right] \text{sec}$$

The apparent velocities 6.66 km/sec and 8.26 km/sec are very close to the velocities found in Fennoscandia for P_b and P_n, respectively (Sellevoll and Warrick 1967). These velocities indicate, therefore, that the depth to the discontinuities is about the same along the profile from the shotpoint to about 200 km southward.

The maximum deviation from the least square fits for P_b and P_n is also given in table 2. The maximum deviations for P_n vary from + 0.09 for all stations except for the stations 411 and 412 where the maximum deviations are respectively +0.47 and +0.54 sec indicating an early arrival. For P_b the maximum deviations vary from +0.11 to -0.09 for the stations 413 to 408. For the four stations 409, 410, 411, and 412 the deviations are +0.50, +0.57, +0.82 and +1.22 sec, respectively.

The strong phases P_{x_1} and P_{x_2} (Fig. II-B. 6) arriving 1 to 3 sec after P_b can not at the moment be given a satisfactory explanation. Phenomena having the same character as observed during this study have been observed in Southern Norway and strong unexplained late arrivals in the P-wave group have also been reported observed from other parts of the world. These phases need a further study.

CORRELATION BETWEEN THE BOUGUER ANOMALIES AND THE RESIDUALS FOR P_b AND P_n.

The Geographical Survey of Norway distributed, in 1963, a gravity map showing the Bouguer anomalies in the Northern Norway. A part of this map is shown in Fig. II-B. 3. This map is based upon gravity measurements made every 2 km along the main roads in that part of the country. The gravity at sea has been measured with a Vening Meinez pendelum on board a submarine laong the coast of Northern Norway.

The contour interval on the map is 10 milligal. The contour lines show that the Lofoten-Vesterålen region belongs to a region with an extremely high positive Bouguer anomaly.

The middle part of Fig. II-B.7 shows a gravity profile from the shot-point to the center of the gravity high in the Lofoten region. The profile is based upon NGO's gravity map. The profile shows that the anomalies increase smoothly from +20 milligal at the shot-point to about 60 milligal at station 413 and smoothly decrease to about 30 milligal at 418; then there is an increase again to about 40 milligal at 403, and a decrease to 20 milligal at 405. From station 405 and southward we find a strong gravity gradient. The Bouguer anomaly reads about +120 milligal at station 412.

Fig. II-B. 7 shows that there is a strong correlation between the Bouguer gravity anomaly and the residuals for P_n and P_b.

THE CRUSTAL STRUCTURE IN THE LOFOTEN-VESTERÅLEN REGION

An attempt has been made to calculate the crustal structure along the profile from the shot point through the zone with the maximum gravity anomaly in the Lofoten region.

The apparent velocities 6.66 km/sec and 8.26 km/sec obtained out to at least 250 km from the shot point correspond very well to the normal velocities obtained throughout Fennoscandia where crustal structures are known to be horizontal. This indicates that the depth to the discontinuities must be about the same along the profile line out to a distance of at about 250 km from the shot point.

From previous work in Fennoscandia a three layer crustal model seems to fit the data obtained. The data collected in this study also supports a three-layer model with the first having a P velocity of approximately 6.1 km/sec, the second layer a velocity of approximately 6.6 km/sec and the third layer a velocity of approximately 8.2 km/sec. The velocities found in this area outside the region of the high gravity gradients (6.1, 6.66, and 8.25 km/sec) indicate horizontal layering along the profile described. Since there are no counter-shot to prove otherwise, it have been assumed a three-layered crustal model with horizontal interfaces for the areas outside the region of high gravity gradients. We also assumed no vertical velocity gradients within each layer.

Under this assumption have been calculated the thickness of layers within the region outside the high gravity gradients to 16.7 km for the first layer and 14.7 km for the second layer. The depth to Mohorovicic discontinuity is consequently 31.4 km.

From the residual values in table 2, the deviation from the horizontal structure has been calculated and displayed in the lower part of Fig. II-B. 7.

The most plausible conclusion that can be drawn from Fig. II-B. 7 is that the very high gravity anomaly at the southern part of the Lofoten - Vesterålen region is, at least partialy,, caused by a thinning of the granitic layer and a shallowing of the Moho-discontinuity under the Lofoten area as compared to the adjoining Vesterålen area.

Shot No.	Δkm	P_g	$\pm\Delta t_g$	P_b	$\pm\Delta t_b$	P_n	$\pm\Delta t_n$	P_{x1}
413	99,19 km	16,59 sec	- 0,06 sec	17,31 sec	0,00 sec			
415	128,19 "	21,27 "	+ 0,07 "	21,75 "	-0,08 "			
417	159,59 "			[illegible]6,26 "	+0,11 "	25,67 sec	+0,03 sec	
418	166,16 "			27,35 "	+0,02 "	26,55 "	-0,06 "	
402								
403								
404	214,67 "			34,66 "	+0,02 "	32,35 "	-0,01 "	
405	2[illegible]5,96 "			36,26 "	+0,06 "	33,64 "	+0,05 "	38,95 sec
407	240,00 "			38,51 "	-0,09 "	35,58 "	- 0,09 "	40,98 "
408	249,23 "			39,37 "	0,00 "	36,55 "	0,0[illegible] "	42,15 "
409	264,09 "			41,62 "	+0,50 "	38,35 "	+ 0,04 "	44,17 "
410	[illegible]66,34 "			41,85 "	+0,57 "	38,60 "	+ 0,04 "	44,45 "
411	282,52 "			44,00 "	+0,82 "	40,12 "	+0,47 "	46,26 "
412	289,29 "			44,70 "	+1,22 "	40,92 "	+0,53 "	47,14 "

Table 2.

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Mr. Arne Øfsthus has given very valuable assistance in the preliminar data preparation. Mr. John Hannha is especially acknowledged for his help and suggestions concerning the seismogram montage program.

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3. Sellevoll, M. A. and Warrick, R. (1967):
Appendix A. (This report.)

4. Sellevoll, M. A. (1967):
Appendix C. (This report.)

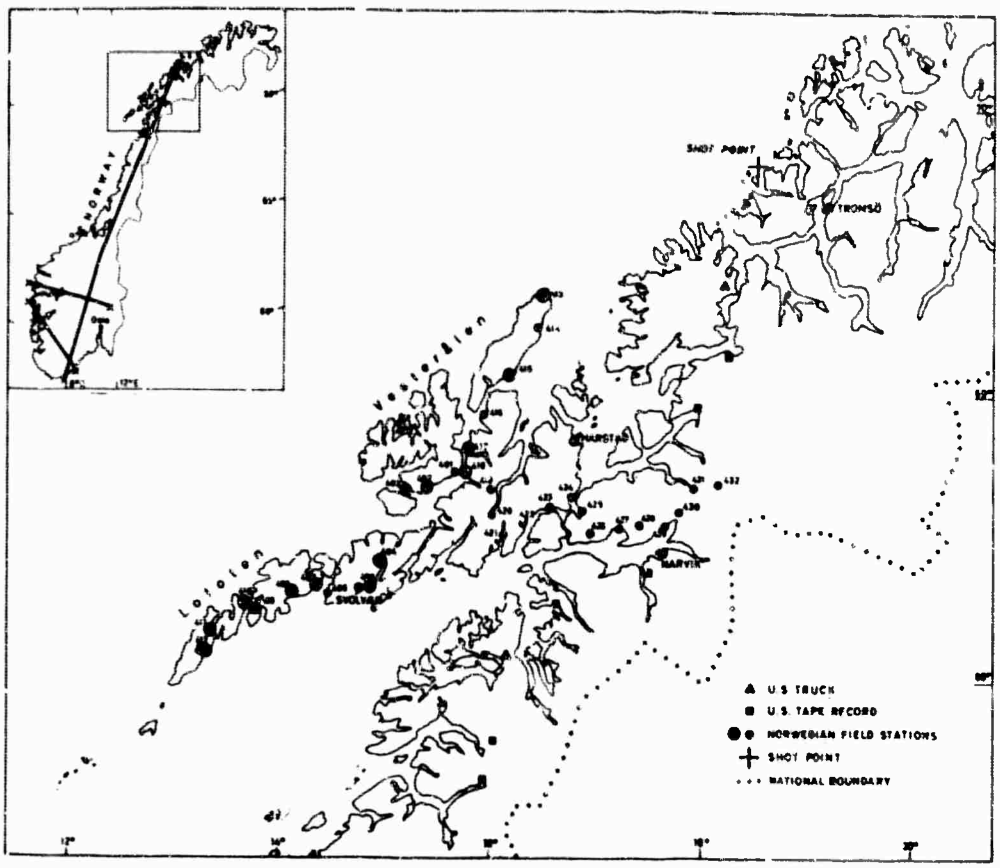

Fig. II-B. 1 : The location of the seismic stations in the Lofoten - Vesterålen region. The stations used in this study are indicated by big filled circles. The shotpoint NW of Tromsø is the only shotpoint utilized in this study.

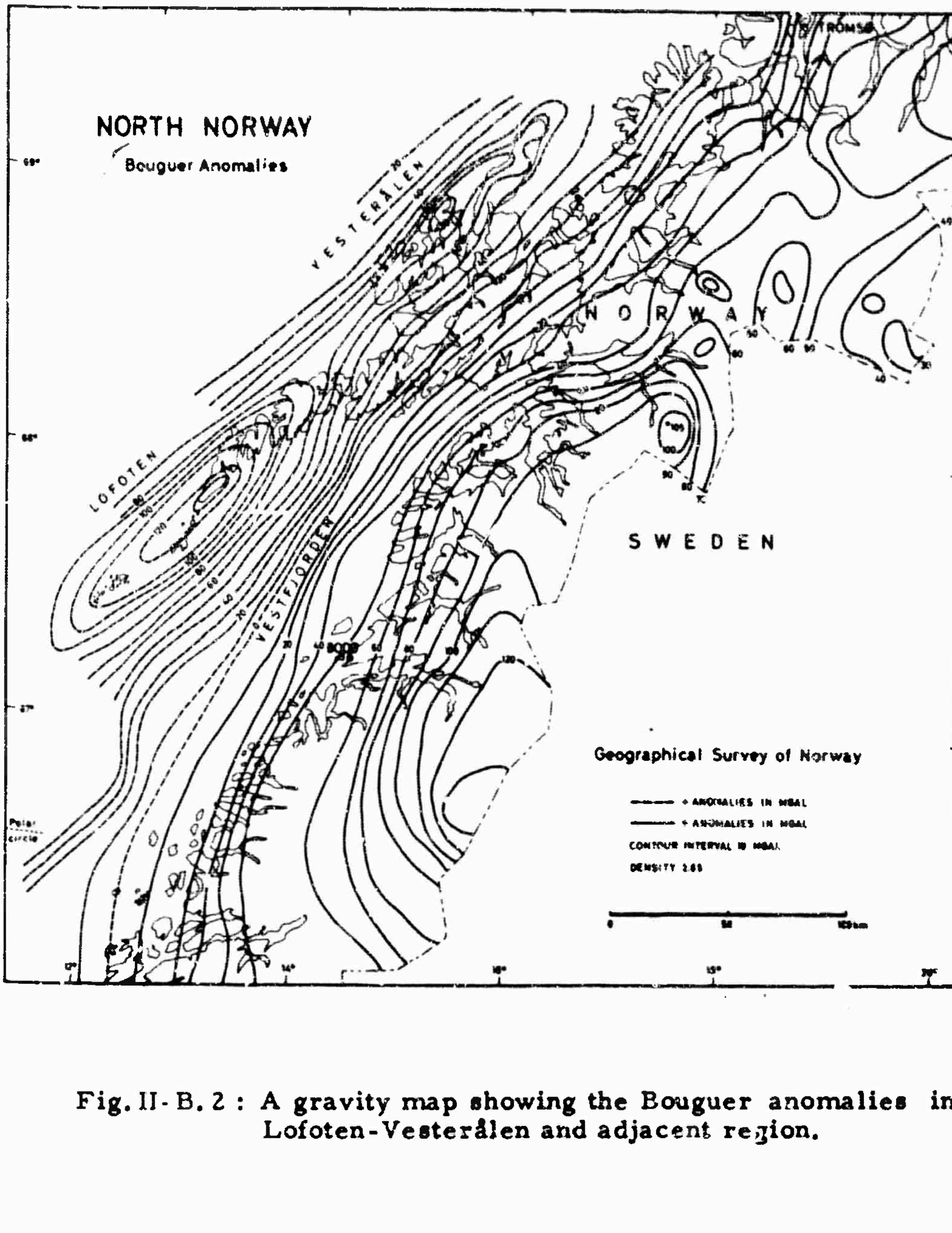

Fig. II-B. 2 : A gravity map showing the Bouguer anomalies in the Lofoten-Vesterålen and adjacent region.

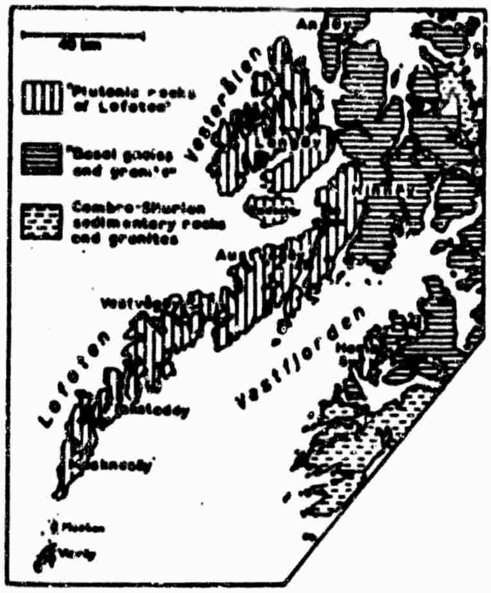

Fig. II-B. 3 : A map showing the field relations between the " plutonic rocks of Lofoten " and the " basal Gneisses" containing metamorphic Caledonian sedimentary rocks.

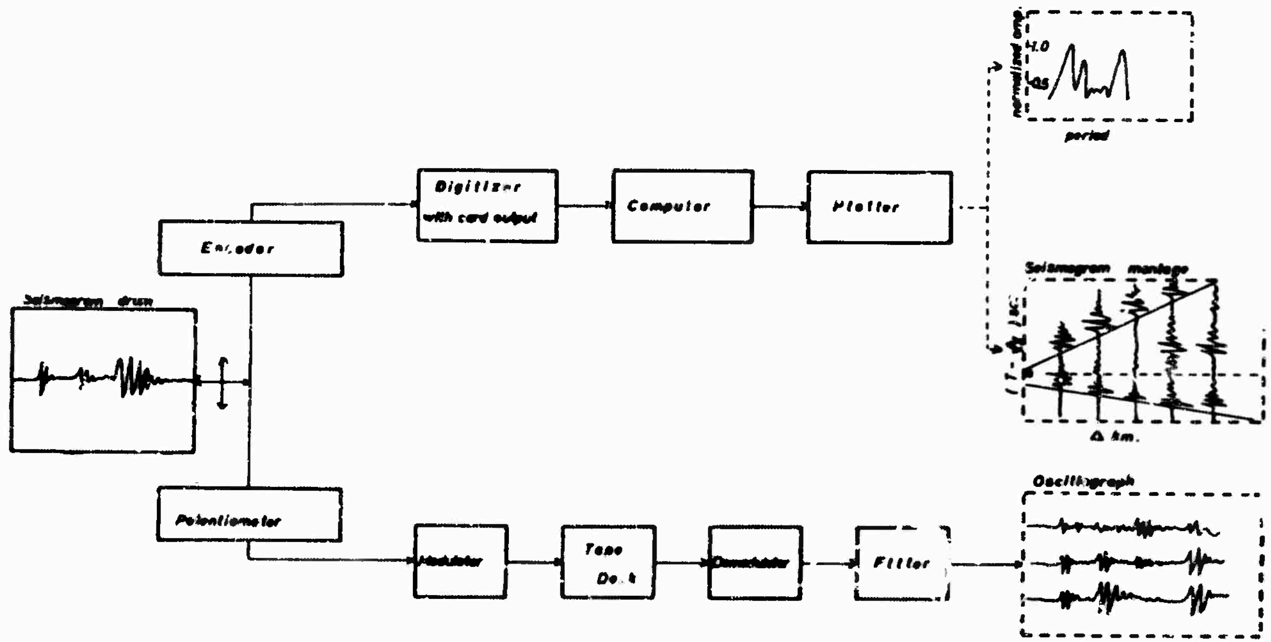

Fig. II-3.4: Block diagram illustrating the data handling methods.

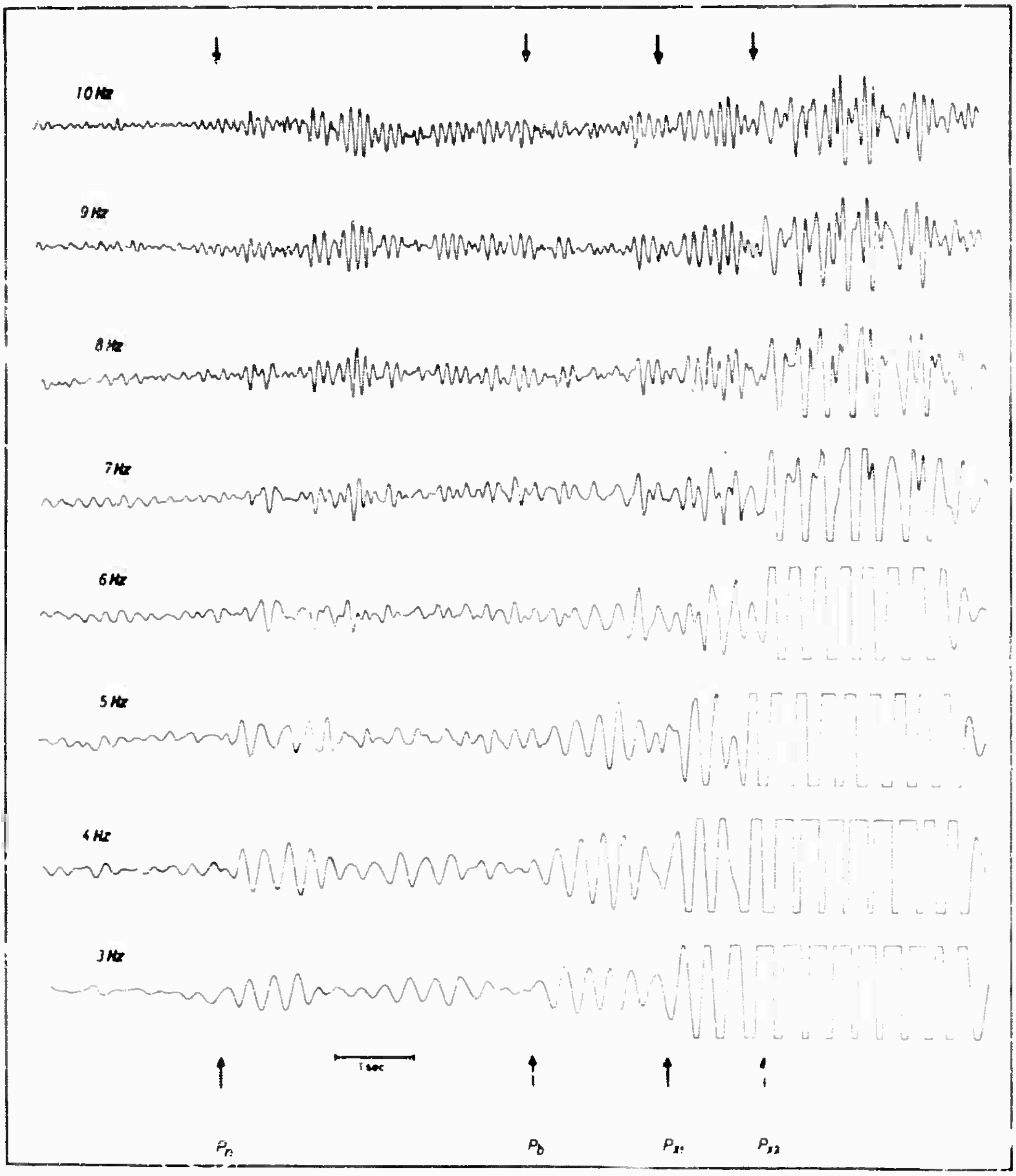

Fig. II-B. 5 : An example of a filtering analysis of the Z-component recording at the station 412 (Δ = 289.29 km).

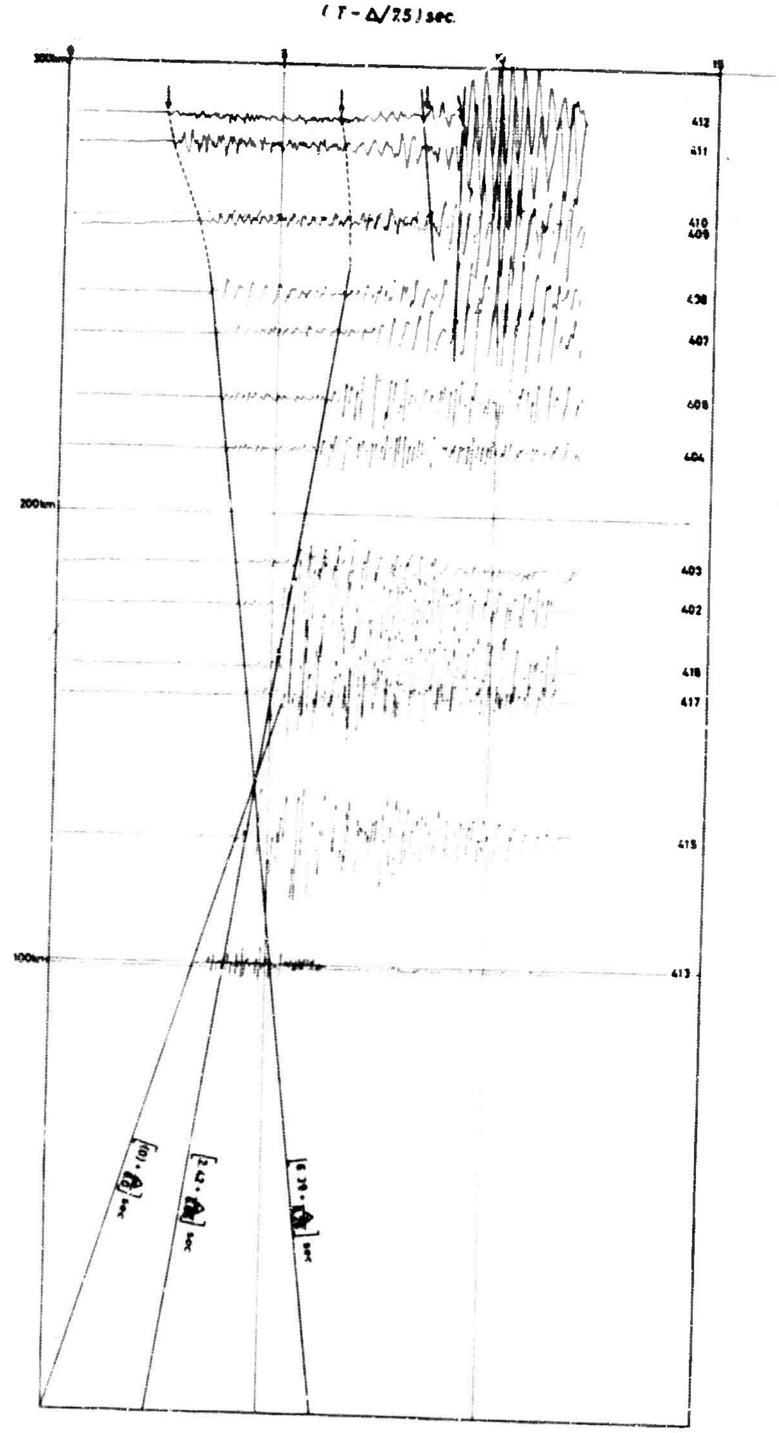

Fig. II-B. 6: A montage of the Lofoten-Vesterålen Z-component seismograms.

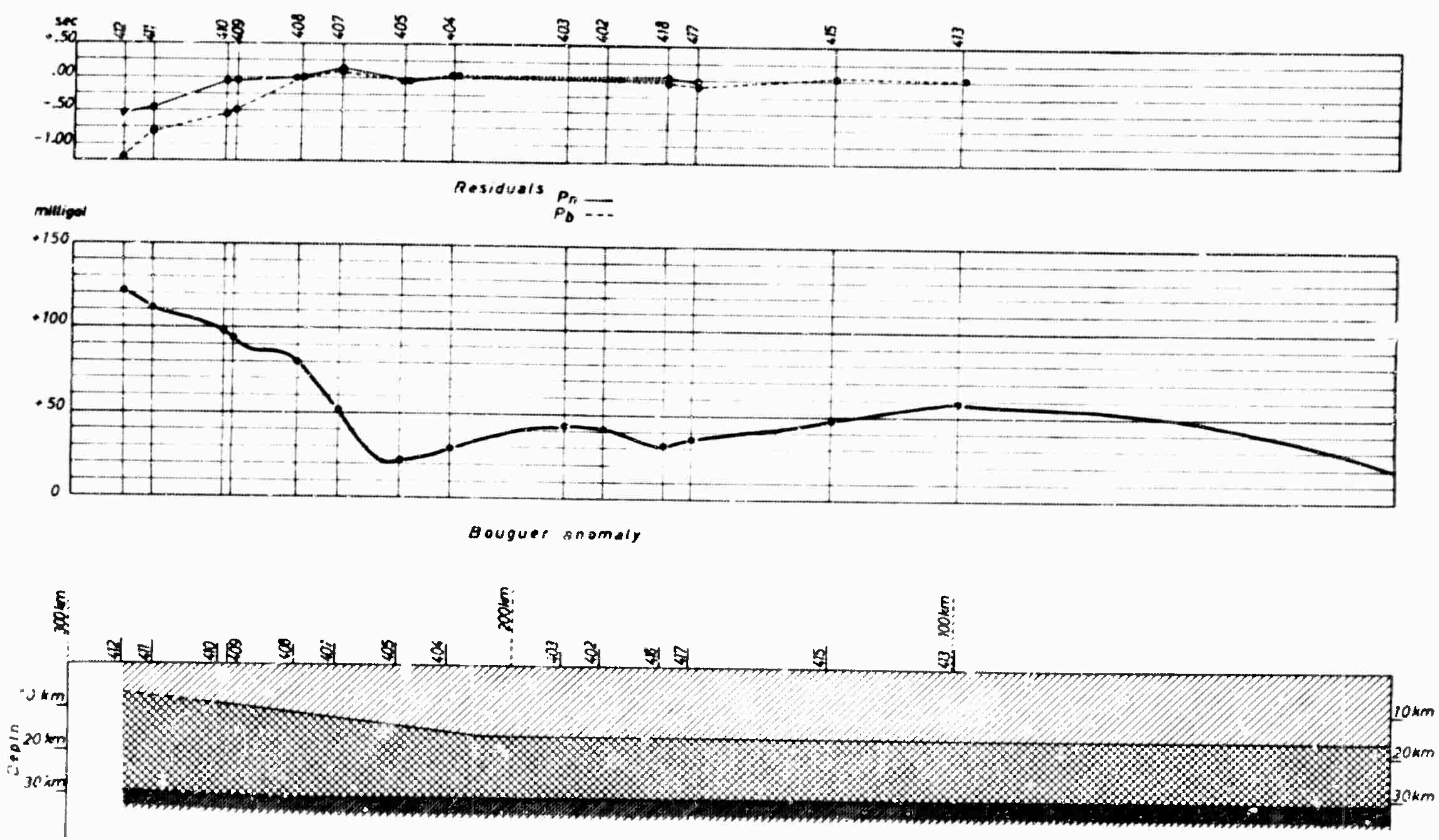

Fig. II-B. 7 : A correlation between travel time residuals, Bouguer anomalies and crustal structure in the Lofoten-Vesterålen region.

APPENDIX C

A TRAVEL TIME AND PHASE IDENTIFICATION STUDY FOR FENNOSCANDIA

by

MARKVARD A. SELLEVOLL

ABSTRACT

The present paper is based on the results obtained during a seismic refraction experiment utilizing 19 explosions detonated in Norway during the period from August 14, to September 4, 1965. In addition to recordings at 20 temporary stations, most of the larger explosions were well recorded at the permanent stations of the Fennoscandian seismological network. The following travel times have been obtained using the network data:

t_{P_n} : $(7.6 + \Delta / 8.20)$ sec $\qquad$ t_{S_n} : $(12.3 + \Delta/4.66)$ sec

t_{P_b} : $(2.3 + \Delta/6.60)$ sec

t_{P_g} : $(0.2 + \Delta/6.13)$ sec $\qquad$ t_{S_g} : $(0.1 + \Delta/3.58)$ sec.

Improvement in phase identification by analog analysis techniques is illustrated using records from the Lillehammer array.

INTRODUCTION

This is one in a serie of papers giving the results obtained during a seismic experiment in Norway which was carried out between August 14, and September 4, 1965. Investigations are beeing carried out under a cooperative program between the U.S. Geological Survey, Branch of Crustal Studies (Menlo Park, U.S.A.) and the Seismological Observatory, University of Bergen (Bergen, Norway). The U.S. Geological Survey operated 12 temporary stations and the Seismological Observatory occupied 8 temporary stations during the experiments.

In all, 19 shots were fired ranging from 150 kg to 9100 kg. 17 of these large explosions were recorded at the permanent stations of the Scandinavian seismological network, and this paper deals with the results of a travel time study based on these recordings.

This paper gives also an example of the improvement in phase identification which can be obtained, especially for later arrivals, by analysing the output of the magnetic tape records in an analog computer using the particle motion technique described by Sutton and

and Pomeroy (1963). A detailed study of the magnetic tape seismograms from the Lillehammer array station is in preparation.

The main purpose of this study is to gain information about the travel times for Fennoscandia so that these data may be used in a forthcoming study to locate epicenters in Norway and adjacent areas based on data from the Fennoscandian seismological network.

A BRIEF DESCRIPTION OF THE GEOLOGY OF FENNOSCANDIA

Fennoscandia is a term proposed by the Finnish geologist W. Ramsay, in 1910 and it includes the geological-geographical unit which comprises the Scandinavian Peninsula, Finland and adjacent parts of the USSR. The entire eastern part of this region, called the Baltic Shield area, is characterized by the predominant occurence of Precambrian rocks.

The western part of Fennoscandia is characterized by Cambro-Silurian rocks (Fig. II-C. 1.) and rocks which have been strongly metamorphosed during the Caledonian orogeny.

The Precambrian rocks in Southern Norway are separated into two parts by the Oslo graben. Towards the north the Precambrian rocks of Southern Norway dip below the younger rocks of the Caledonian orogenic zone, which comprise the greater part of Norway.

The Scandinavian Caledonides consist of geosynclinal sedimentary and volcanic rocks. An increasing degree of metamorphism with granitization and intrusions can be clearly seen from the Oslo graben towards the northwest. It is to the northwest that the deep-seated orogenic processes have been especially active and here the rocks of the previous Precambrian basement and mainly Cambro-Silurian sedimentary rocks have been strongly altered and welded together.

The Caledonides continue from Northern Norway to the Svalbard region. The southward continuation is more uncertain. It is most likely that the main branch of the Caledonides continues to Scotland, but there are, in addition, some indications that at least a minor branch of the Caledonides continues south-southeast below the Mesozoic and Tertiary rock formations in Denmark and Northern Germany.

On the Scandinavian Peninsula mainland only two relatively smaller regions with Mesozoic rocks are known, Scania (Sc in Fig. II-C. 1.), the southernmost part of Sweden and on the Island Andöya (A in Fig. II-C. 1.) in Northern Norway. There the sediments have been preserved between faults.

DATA

Table 1. gives the shotpoint coordinates, date, time, water depth

and charge in kg for each of the explosions. All shots were fired on the sea floor. (Except the Åsnes shot, which was fired in a swamp)

Positions were determined in each case by triangulation using shore points. The distances to these points were, in general, short (except Grimstad 04 GMT - 9. 3. 1965) so that the inaccuracies in the position determination should be less than 100 m.

The shot instant in universal time was obtained by recording radio time signals together with the electrical indication of the shot instant.

Fig. II-C. 2. shows the seismological station network in Fennoscandia together with the explosion sites used for this study. The stations used for this study are indicated in Fig. II-C. 2 as closed circles, the other stations are indicated with open circles.

Table 2 gives the station name, the abbreviation, the coordinates and height in meters for stations from which seismograms have been studied.

A list (Table 4) has been prepared showing the instrumentation and instrument constants for the station used in this study.

THE TERMINOLOGY

Various proposals have been made in recent years to revise or replace the traditional terminology of longitudinal and transverse waves within the crust. No rigid standards of terminology have been established.

In Scandinavia almost everywhere old crystalline rocks occur up to the surface, covered only by a few meters of recent unconsolidated material. The terms have been used with the following meaning:

P_g (S_g) : A compressional (shear) wave that has travelled through a layer of a few hundred meters of low-velocity crystalline rocks and then refracted into a layer with a velocity of 6.0 - 6.20 km/sec. (3.50 - 3.60 km/sec.),

P_b (S_b) : A compressional (shear) wave that has penetrated through the uppermost layer and then refracted into a deeper layer of the crust at velocities ranging from 6.4 - 6.8 km/sec. (3.50 - 3.60 km/sec.).

P_n (S_n) : A compressional (shear) wave that has penetrated through the crust and has travelled as a refracted wave in the upper mantle rocks at velocities ranging from about 8.00 to 8.30 km/sec. (4.5 - 4.8 km/sec.).

L_g : A wave with predominantly SH or Love-type particle

motion. The wave is a surface wave component of S_g, propagated to great distances by wave guide mechanisms in the silicic crust with a velocity about 3.55 km/sec. (Press and Ewing, 1952, Båth, 1954, Oliver 1955).

CALCULATIONS

From the Swedish stations 16 mm film copies of all Z-component seismograms were available, however, these copies were not easy to read with sufficient accuracy. At Dr. Båth's suggestion we used his data given in August and September bulletins from the Seismological Institute, Uppsala. Dr. Båth's phase identifications have been used in most cases, but some phases which do not fit into the travel time diagrams have been reidentified or omitted.

Copies of the seismograms from the Finnish stations and original seismograms from the Norwegian stations have been studied.

Table 3A shows the travel times obtained from the Tromsø shotpoint. Table 3B includes the travel times obtained from the two shot-points Kristiansand and Grimstad on the southern and the southeastern coast of Norway. Table 3C includes the travel times from the two shotpoints Fedje and Flora on the western coast of Southern Norway, together with the travel times which were obtained at Lillehammer from the Åsnes shotpoint. The Lillehammer array station was the only station which recorded the events from the Åsnes shotpoint.

On the basis of the data presented in Tables 3A, 3B and 3C, the least square fits to a straight line which have been calculated by the different phases.

$t = I + \Delta/V$ sec (RMSE)

t = travel time

I = intercept time

RMSE = root mean square

Δ = distance

V = velocity

P_n phase:

The readings from (1) the Tromsø shotpoint, (2) the Kristiansand and Grimstad shotpoints, and (3) the Fedje and Flora shotpoints have been investigated separately for the phase P_n and S_n. The results of all computations made are presented in Table 5.

Table 5 shows that the apparent velocities obtained from the shotpoints in Southern Norway are slightly higher than the velocity

obtained from the Tromsø shotpoint in Northern Norway. If this is due to variations in the crustal structure and/or variations in the velocity in the Upper Mantle, can not be stated on the basis of these data. All P_n readings together gave the following results:

$$t_{P_n} = (7.6 + \Delta/8.20)\text{sec}. \qquad (1.1\ \text{sec})$$

P_b phase:

A strong phase is seen to follow the P_n phase in many seismograms. This phase has been identified as P_b. Fig. II-C. 3 shows an example of the recordings of this phase at the Lillehammer array station. This phase can be seen as a very strong arrival on almost all Lillehammer seismograms obtained from the four shotpoints on the coast of Southern Norway.

The Lillehammer array station lies within the distance range of 317 to 373 km from the shotpoints on the coast of Southern Norway. The P_b wave is usually a difficult wave to detect and it is therefore surprising to find a P_b phase with such relative large amplitudes. The head-wave P_b should decrease in amplitude relatively rapidly beyond the critical angle. A reflection from the Moho should have approximately the same travel time as P_b in the above mentioned distance range and therefore a Moho-reflection cannot be excluded. However, the amplitudes and the travel times of this phase can easily be studied using observations from the temporary stations that were in operation in Southern Norway during this experiment. These phases will be studied in greater detail in a subsequent paper in this series. All readings of the phase identified as P_n gave the following result:

$$t_{P_b} = (2.3 + \Delta/6.60)\ \text{sec}. \qquad (1.4\ \text{sec})$$

P_g phase:

From seismic velocity measurements in surface rocks, it seems that velocities between 5.0 and 5.5 km/sec are very commonly obtained all over Scandinavia. These velocities increase downward within a few hundred meters to about 6.0 – 6.2 km/sec. A phase with this velocity has been observed as the first arrival up to a distance range of 80 to 90 km during previous refraction crustal studies in Scandinavia. The amplitude of the P_g phase decreases relatively rapidly and the P_g phase is seldom detectable after the crossover with P_b (80 – 90 km).

Observations of P_g made during the present study for distances less than 100 km give the following result:

$$t_{P_g} = (0.2 + \Delta/6.13)\ \text{sec} \qquad (1.2\ \text{sec})$$

In many seismographs a phase that fits relatively well to the least square fit given for P_g is observed as a later arrival out to about 950 km. If all of these data are taken together, the following result is obtained:

$$t_{(P_g)} = (0.7 + \Delta/6.19) \text{ sec.} \qquad (1.2 \text{ sec})$$

S_n phase:

This phase has been recorded in 85 cases and the following least square fit to these data has beeb obtained:

$$t_{S_n} = (12.3 + \Delta/4.66) \text{ sec} \qquad (2.9 \text{ sec})$$

On a travel time diagram a line that defines the S_b phase is not observed. It should be stressed, however, that from the analysis of the data from the Lillehammer array station it is very difficult to identify phases within the S group from a usual seismogram.

S_g / L_g phase:

These phases are usually the strongest observed in the seismograms. M. Båth (Seismological Institute, Uppsala, Seismological Bulletin, August 1965) has found by comparing the records from the Swedish stations of the explosions at the Flora shotpoint on 28 and 29 August 1965 that S_g dominates at distances $\Delta < 5^o$, that S_g and L_g can exist together at $5^o - 7\frac{1}{2}^o$, and that L_g dominates at greater distances. For this reason, the calculation of the least square fit for S_g has been based on the readings from distances less than 500 km. The following result was obtained:

$$t_{S_g} = (0.1 + \Delta/3.58) \text{ sec} \qquad (2.0 \text{ sec})$$

The readings above 500 km that fit relatively well to this line have been put into Tables 3 A - 3 C in parentheses.

PHASE IDENTIFICATION BASED ON ANALYSIS OF MAGNETIC TAPE SEISMOGRAMS FROM THE LILLEHAMMER ARRAY STATION

Identification of later arrivals on seismograms from local events recorded at typical seismological stations is, in many cases, difficult and at best uncertain. This is especially true for the S and sur-

face wave groups. Recording events on magnetic tape at an array station makes it possible to improve the phase identification. In this paper an example will be given demonstrating the feasibility of phase identification on the basis of particle motion at the Lillehammer array station.

The Lillehammer array station is located about 120 km north of Oslo. Fig. II-C. 4 shows the array pattern for the station. The short-period seismometers used are the Benioff type (Geotech models 1051 and 1101). The output of these instruments is amplified by phototube amplifiers. The data are recovered on a 14-channel Ampex Model 314 analog magnetic-tape recorder. The recordings are made at a tape speed of 0.3 inch per second. In addition to this recording, the individual seismometers Z 1 - Z 7, the SPT and SPR, timing, and the sum of Z 1 - Z 7 are recorded on a 16 mm film recorder with a recording speed of 30 mm/min. A 35mm film recorder records SPZ3-SPR-SPT and timing. Time pulses are recorded on the film and magnetic tape every 10 sec.

A method for separating earthquake phases using rotating of axes and particle motion has been described by Sutton and Pomeroy (1963). The same method has been applied to some of the magnetic tape recordings from the seismic experiment in Norway in 1965.

The method used is to play the output of the magnetic tape seismograms into potentiometers in the analog computer EAI - TR - 48. The potentiometers' values are set to the sine and cosine of the angle between the SPR north direction and to the event under study (positive to right). Pure longitudinal and transverse traces are produced from the N-S and E-W recorders by the transformation

$$T = N \sin\theta - E \cos\theta$$

$$L = N \cos\theta - E \sin\theta$$

where T is the transverse record and L is the longitudinal record. When the vertical and longitudinal traces are multiplied together, the product, LZ, defines „away" and „up" motion as positive. This product LZ is positive for compressional-type particle motion and negative for SV-type particle motion. Pure Raleigh wave motion alternates in the positive and negative directions at twice the original frequency. This procedure separates surface particle motions of the following types:

1) transverse or SH (T),
2) vertically polarized-transverse or SV,
3) longitudinal horizontal (L) and
4) compressional (Z).

A brief discussion of the instrumentation principles and of the effects

of differences in instrumental amplitude and phase response on this procedure is given by Sutton and Pomeroy (1963).

In Fig. II-C. 5 an example of the use of this procedure is given. Playback recordings of the SPZ3, SPR and SPT seismograms, with a speed up factor of 20, are shown in the three top traces. No filtering was used during the playback. The next two traces show the transverse (T) and longitudinal horizontal (L) motion. The P-wave group is much weaker on the transverse component, as expected. As mentioned earlier, the P_n wave is surprisingly weak compared with the head wave P_b or Moho-reflection. The second trace from the bottom (LZ) shows that at this particular gain setting P_n can hardly be recognized, but the later part of the P group is very clearly defined. On all traces in Fig. II-C. 5 onsets can be seen proceeding S_n. The (LZ) trace shows that these onsets are of both P and S - wave types. The S_g wave forms a distinct onset on the (LZ) trace. The S_g phase shows very clearly on this trace as the strongest phase in the seismograms.

By comparing Fig. II-C. 5 with Fig. II-C 3 the improvement of the phase identification for the S-wave group can clearly be recognized.

CONCLUSIONS AND DISCUSSIONS

The seismic phase velocities which have been obtained during the present study are presented in Table 6, column I. Table 6, column II includes average velocities, given by Penttillä (1965), obtained during recent years in seismic refraction studies in Finland. In column III are given seismic velocities calculated by Sellevoll and Kanestrøm (1967,) on the basis of travel times from an earthquake that occured on the coast outside Northern Norway and which was very well recorded by the Scandinavian seismological stations. In column IV are given some velocities reported by Sellevoll and Penttilä (1964) obtained during seismic refraction measurements in Northern Norway. The shotpoint was then located 44 km northwest of Tromsø and the recordings were made at four stations only, between Tromsø and Muonio in Finland (Fig. II-C. 1).

From seismic refraction measurements in Jutland, (Denmark) Hirschleber, Hjelme and Sellevoll (1966) have obtained the following P-velocities beneath a thick (some km) sedimentary layer: 6.1 - 6.6 and 8.1 km/sec.

The average P_n and S_n velocities for Fennoscandia given in Table 5 are very close 8.20 and 4.65 km/sec respectively. The present study indicates that the velocity for P_n as well as for S_n is slightly higher from the shotpoints in Southern Norway than from the shotpoint in Northern Norway. But the variation in the velocities for P_n and S_n within Fennoscandia seems to be very small.

The present study shows a P_b velocity of 6.6 km/sec. This velo-

city, as well as th P_g velocity, is in very good agreement with what have been found in Finland and Denmark during refraction studies.

The average apparent P-velocities for Fennoscandia obtained during this study fit the following model, assuming horizontal layers and constant velocity within each layer:

1. layer ca	19 km
2. layer ca	19 km
Thickness of the crust	38 km

An attempt has been made to correlate the velocity obtained in Fennoscandia (The Baltic Shield) with the velocities obtained in the Canadian Shield.

Table 6, columns VI, VII and VIII includes data which were obtained by Hodgson (1953 a and 1953 b) and Hall and Brisbin (1961) during seismic refraction studies in the Canadian Shield.

Brune and Dorman (1963) have found, by measurements of phase velocities in the Canadian Shield, that phase and group velocities are higher than yet found in any other continental area. They found predominant L_g arrivals with a velocity of about 3.65 km/sec and an S_n arrival is recorded clearly to distances of about 4000 km with a velocity of about 4.72 km/sec. By fitting a theoretical model to the phase velocity data, Brune and Dorman obtained the best fit for a three-layered crust consisting of a 6 km layer of shear velocity 3.64 km/sec. and an 18.2 km layer of shear velocity 3.85 km/sec.

From Table 6 it can be seen that 8.20 km/sec is a very well established phase velocity for P_n both in Fennoscandia (the Baltic shield) and the Canadian shield.

On the basis of travel times from explosions, Hodgson (1953 a and b), Hall and Brisbin (1961) have found a phase with a velocity of 7.10 km/sec. in the Canadian shield. Such a high velocity is not, in general, observed in the layer just above the Moho in Fennoscandia. In one case, Sellevoll and Kaneström (1967), however, a velocity of 7.39 km/sec. with a corresponding shear wave with a velocity of 4.21 km/sec is reported observed in Fennoscandia. The usually observed P velocity in the layer just above the Moho in Fennoscandia averages about 6.60 km/sec. Concerning this layer just above the Moho there seems to be a difference between Fennoscandia and the Canadian shield.

The P_g values given in Table 6 indicate that the P_g velocity may be slightly higher in the Canadian shield than in Fennoscandia.

The S_n velocity for Fennoscandia seems to be 4.66 km/sec. Hodgson (1953 a) has found, from rockburst studies, an S_n velocity of 4.85 km/sec for the Canadian shield. Hall and Brisbin (1961), who based their study on time blasts, obtained the velocity of 4.60 km/sec

Brune and Dorman found that 4.72 km/sec gave the best fit for their data. This indicates that the S_n velocities obtained in Fennoscandia and the Canadian shield are the same or very close to each other.

The S_b wave, which corresponds to P_b, is very difficult to identify within the shear wave group. On the basis of Finnish data, the average velocity obtained for this phase is 3.75 km/sec for Finland.

The S_g velocity given for Fennoscandia and the Canadian shield shows some scatter. But the average values (Table 6), however, seem to be almost the same for the two regions. Of great interest here is to mention that Brune and Dorman, on the basis of their phase velocity data, found that a model with a 6 km upper crustal layer and a shear velocity of 3.47 km/sec and a second layer of 10.5 km with a shear velocity of ?.64 km/sec gave the vest fit for their data from the Canadian shield.

It should be mentioned that the present travel time study includes not only data from the Baltic shield, but also from its border zone, the Caledonides, which was mainly developed during the Cambro - Silurian geological period.

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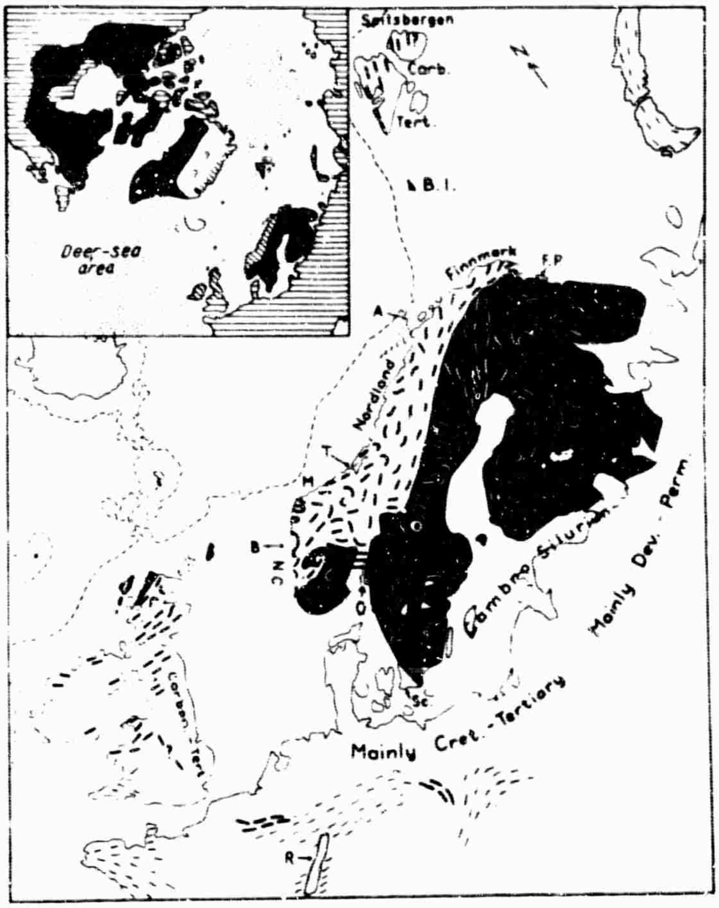

Northwestern Europe with some main structural lines of Precambrian (white lines), Caledonian (thick black lines), and Variscian (Hercynian) orogenies. Small white angular areas and white ring in the Precambrian of Sweden: down-faulted Cambro-Silurian. B.I.-Bear Island, F.P.-Fisherman's Peninsula, A-Andøy (with Mesozoic rocks), T-Trondheim, M-Møre, B-Bergen, N.C.-Norwegian Channel, O-Oslofjord, Sc.-Scania, R-Rhine Graben. In the sea area the 500 m depth-contour line has been drawn and, off southwestern Norway, also the 200 m line. — Inset: map showing in black Precambrian of Canadian and Baltic Shields (E. Suess), furthermore Greenland Precambrian, and (oblique hatching) Caledonides of E Greenland and NW Europe.

Fig. II-C. 1

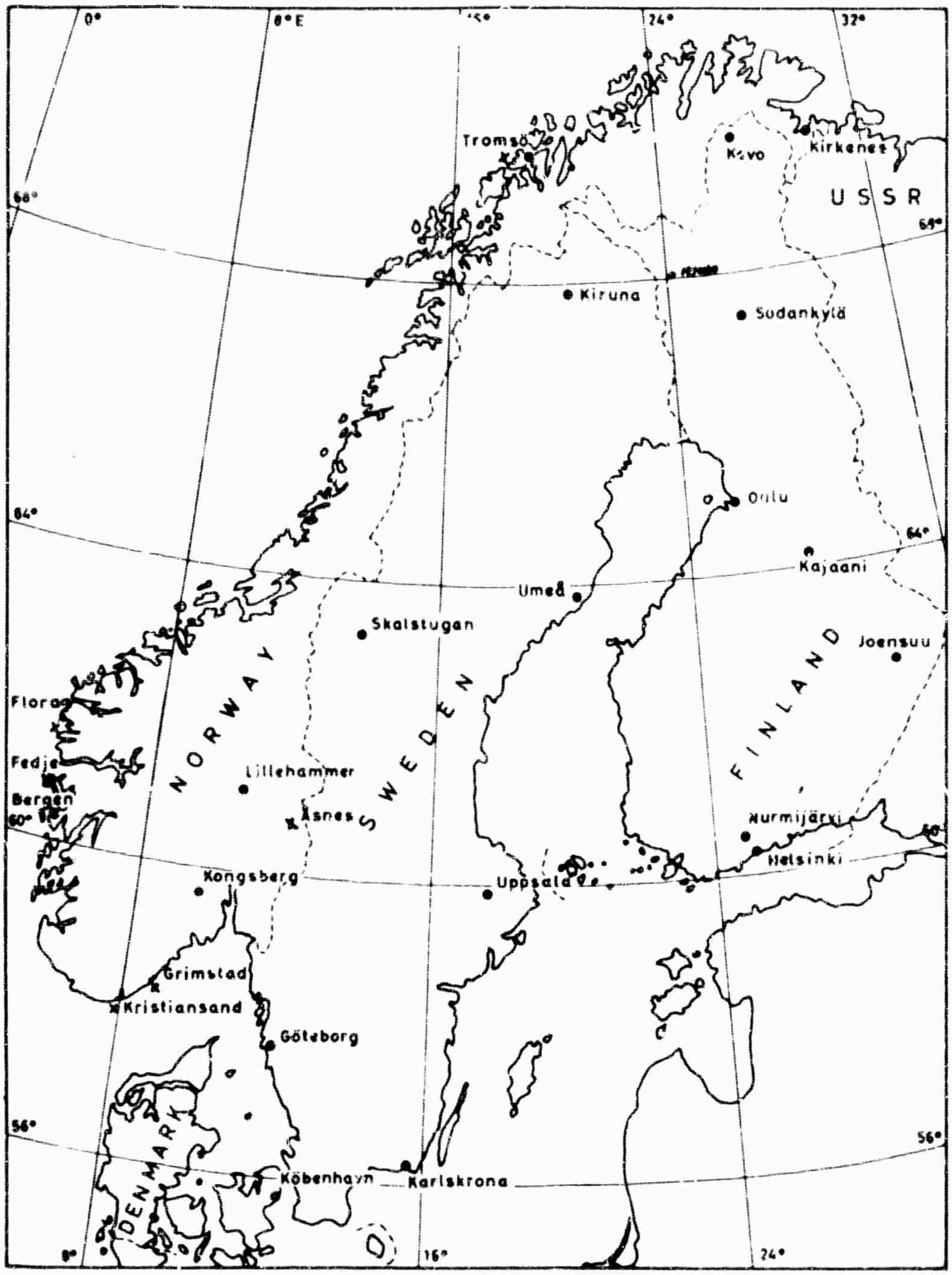

Fig. II-C. 2: Locations of seismic stations and shotpoint utilized in this study. Geographical coordinates for the seismic stations and shotpoints are given in Table I and II.

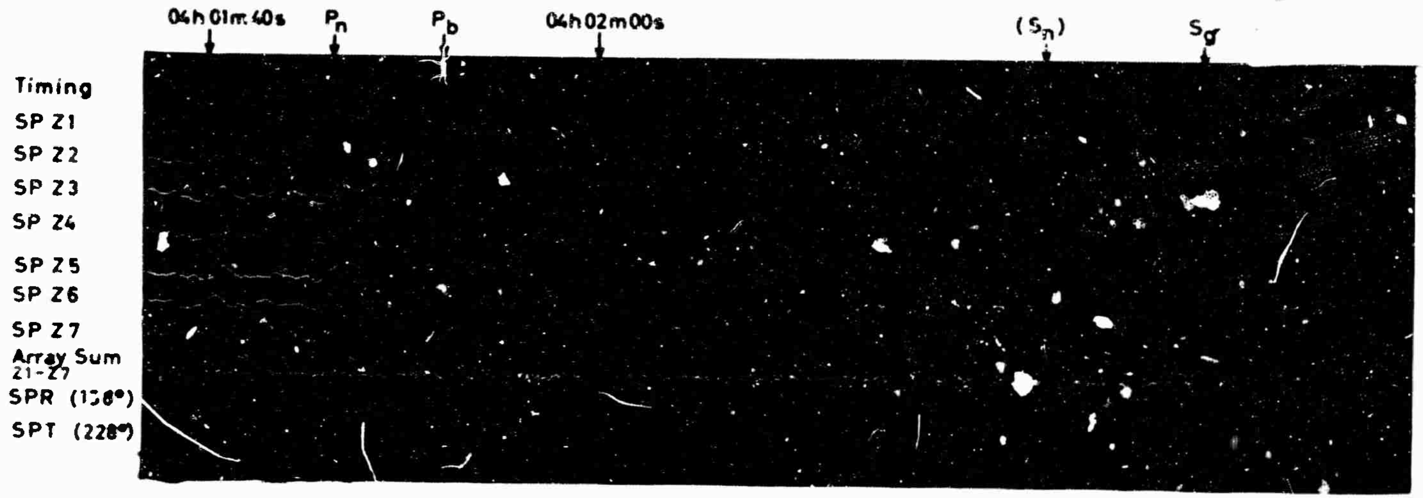

Fig. II-C. 3: Copy of the 16 mm film recording obtained at the Lillehammer array station from the Flora explosion on 29 August, 1965. (Δ = 317.21 km).

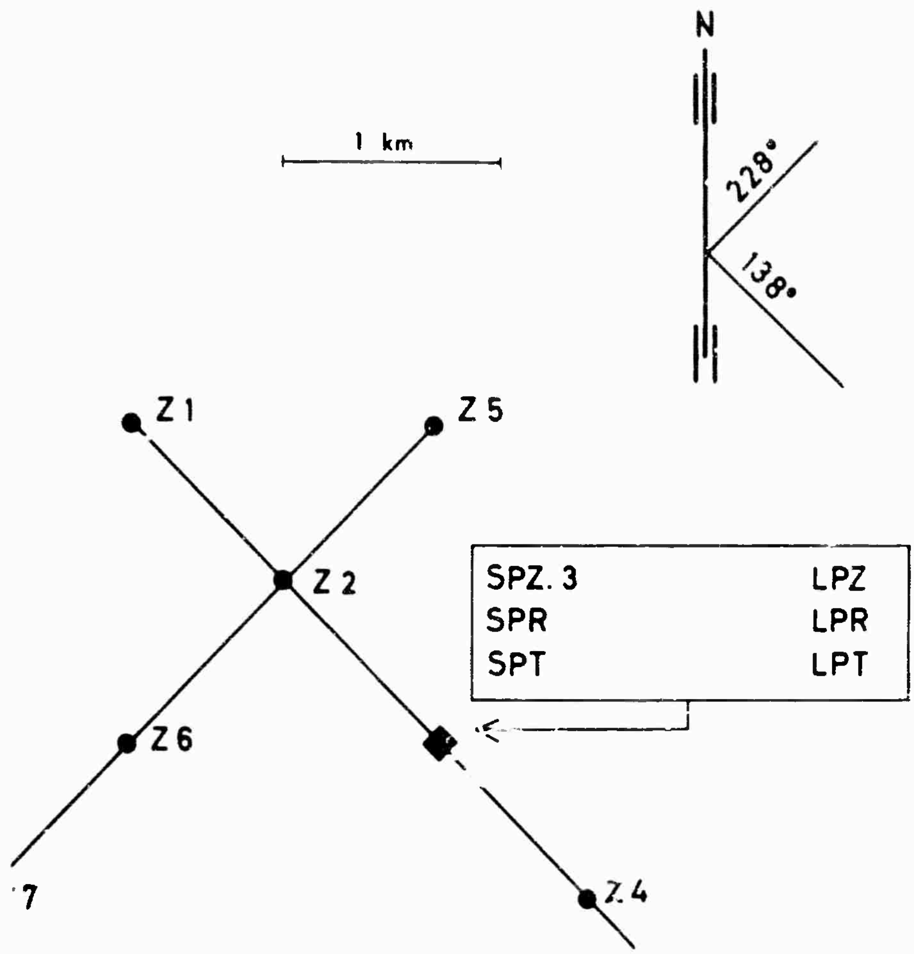

Fig. II-C. 4: Arrangement of the recording site at the Lillehammer seismological array station.
Z 1 ··· Z 7 Short period vertical recording sites.
Positions Z2: 61°03' 17" N, 10° 51' 58" E H=555 m.

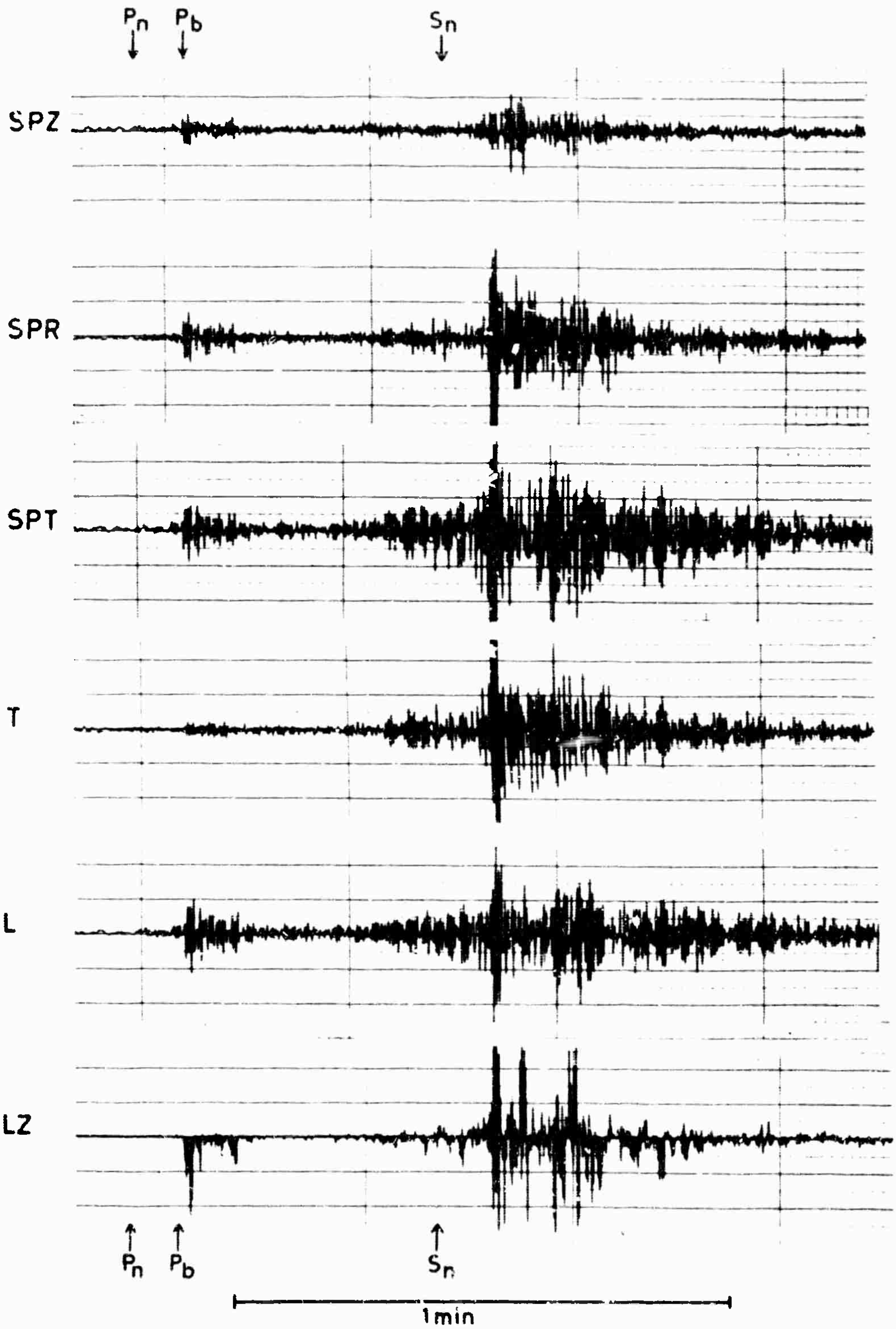

Fig. II-C. 5: Seismograms from the Flora explosions on 29 August, 1965 illustrating separation of longitudinal and horizontal motion and P and SV types of particle motion (Δ = 317.21 km). The sensitivity on S + Z is only 50% of SPR, SPT, T and L).

APPENDIX C

TABLES

1–6

STATION	ABBREVIATION	COORDINATES		HEIGHT (m)
BERGEN	BER	60 23.13 N	5 19.33 E	97
GÖTEBORG	GOT	57 41.54 N	11 58.42 E	66
HELSINKI	HEL	60 10.32 N	24 57.25 E	20
JOENSUU	JOE	62 39.06 N	29 41.42 E	90
KEVO	KEV	69 45.21 N	27 00.45 E	97
KIRUNA	KIR	67 50.24 N	20 25.00 E	390
KAJAANI	KJN	64 05.07 N	27 42.43 E	250
KARLSKRONA	KLS	56 09.51 N	15 35.30 E	11
KONGSBERG	KON	59 38.57 N	9 37.55 E	200
KIRKENES	KRK	69 43.27 N	30 03.45 E	25
LILLEHAMMER 23	LHN	61 02.57 N	10 52.48 E	505
NURMIJÄRVI	NUR	60 30.32 N	24 39.05 E	102
OULU	OUL	65 05.07 N	25 53.47 E	60
PORVOO	POR	60 18.00 N	25 54.00 E	
SKALSTUGAN	SKA	63 34.46 N	12 16.28 E	580
SODANKYLÄ	SOD	67 22.16 N	26 37.45 E	181
TROMSØ	TRO	69 37.57 N	18 55.41 E	15
UMEÅ	UME	63 48.54 N	20 14.12 E	15
UPPSALA	UPP	59 51.29 N	17 37.37 E	14

Table 2: Data on seismograph stations used in this study

STATION	DATE	TIME	POSITION		DEPTH	CHARGE
TROMSØ	14/8 65	04 01 00.02	69 47.40 N	18 16.10 E	108	1820
TROMSØ	16/8 65	04 01 00.33	69 47.40 N	18 15.50 E	117	4550
TROMSØ	18/8 65	04 01 00.33	69 47.35 N	18 16.00 E	120	9100
KRISTIANSAND	18/8 65	04 30 00.43	58 01.23 N	8 03.52 E	96	1820
TROMSØ	20/8 65	04 01 00.33	69 47.30 N	18 15.90 E	108	1950
KRISTIANSAND	20/8 65	04 30 00.30	58 01.23 N	8 04.32 E	115	1820
KRISTIANSAND	21/8 65	04 30 00.83	58 01.23 N	8 04.32 E	83	1360
FLORA	28/8 65	05 01 00.20	61 28.85 N	5 02.45 E	65	1820
FLORA	29/8 65	04 01 00.18	61 28.90 N	5 02.30 E	86 (?)	1820
FLORA	30/8 65	04 01 00.07	61 28.90 N	5 02.50 E	80	2880 (?)
ÅSNES	30/8 65	04 29 59.[illegible]	60 39.88 N	11 52.53 E	5	600
FEDJE	2/9 65	04 01 00.10	60 49.82 N	4 49.63 E	102	1820
FEDJE	3/9 65	04 01 00.17	60 49.82 N	4 49.53 E	102	1820
GRIMSTAD	3/9 65	04 30 00.38	58 17.30 N	8 40.34 E	75	1820
GRIMSTAD	3/9 65	16 01 32.26	58 17.80 N	8 34.20 E	79	1820
FEDJE	4/9 65	04 01 00.13	60 49.88 N	4 49.53 E	102	1820
GRIMSTAD	4/9 65	04 30 00.34	58 18.03 N	8 35.72 E	69	1820

Table 1: Data on the explosions.

STATION	DATE		DIST(KM)	PN	PB	PG	SN	SB	SG
TRO	14/8	TR	31.76			5.3 (0.0)			
KIR	14/8	TR	234.42	36.6 (0.4)					66.9 (1.3)
KEV	14/8	TR	337.13		54.2 (1.1)	56.7 (1.5)	82.7 (-1.9)	(91.2)	95.7 (1.4)
SOD	14/8	TR	434.13	61.7 (1.1)	69.2 (1.5)		106.2 (0.7)		119.2(-2.1)
OUL	14/8	TR	617.20	82.2(-0.6)		99.1(-1.[illegible])	(144.0)(-0.7)	(1[illegible]9.2)	169.4(-3.1)
UME	14/8	TR	672.53	91.2 (1.5)					189.5 (1.5)
KAJ	14/8	TR	756.65	100.5 (0.6)			(175.5)(0.8)	(204.5)	
JOE	14/8	TR	944.36	123.0 (0.2)			(217.4)(2.4)	(260.4)	[illegible].4(13.5)
LHN	14/8	TR	1031.50	134.7 (1.3)			(236.4)(2.7)		[illegible]1.6 (3.5)
POR	14/8	TR	1104.10	143.[illegible] (0.8)			(250.6)(1.3)		
TRO	16/8	TR	31.37			5.3 (0.0)			
KIR	16/8	TR	234.48	36.7 (0.5)					54.4(-1.2)
KEV	16/8	TR	337.26	49.3 (0.7)	58.2 (1.1)	56.7 (1.4)	84.0(-0.6)	(91.5)	95.7 (1.3)
SOD	16/8	TR	434.24	61.7 (1.1)	69.7 (2.0)	73.7 (2.6)	106.2 (0.7)	(114.7)	119.2(-2.1)
KRK	16/8	TR	454.98						127.7 (0.5)
OUL	16/8	TR	617.4	82.2(-0.6)		99.1(-1.5)	(144.0)(-0.7)	(159.2)	169.4(-3.1)
UME	16/8	TR	672.55	91.0 (1.3)					187.9 (0.0)
SKA	16/8	TR	741.16	99.3 (1.3)			(174.0)(2.6)		207.6 (0.4)
KAJ	16/8	TR	756.73	100.7 (0.8)			174.7 (-1)	(204.2)	213.2 ([illegible].7)
JOE	16/8	TR	944.44	122.8 (0.0)			(217.3)(2.3)	(259.8)	276.8(12.9)
LHN	16/8	TR	1031.45	132.7 (1.3)			(236.4)(2.7)		291.8 (3.5)
POR	16/8	TR	1104.70	144.6 (2.2)			(257.6)(3.2)	(301.6)	320.6(11.9)
UPP	16/8	TR	1108.12						316.6 (6.9)
TRO	18/8	TR	31.26			[illegible].3 (0.0)			
KIR	18/8	TR	234.37	36.8 (0.6)					65.4(-0.[illegible])
KEV	18/8	TR	337.20	49.7 (0.9)	54.5 (1.4)	56.5 (1.2)	82.3(-2.1)	(98.2)	95.2 (0.9)
SOD	18/8	TR	434.14	61.2 (0.6)	69.2 (1.5)	72.2 (1.1)	106.7 (1.2)	(115.2)	119.2(-2.1)
KRK	18/8	TR	454.92						126.7(-0.4)
OUL	18/8	TR	617.09	84.2 (1.3)		100.4(-0.4)	(146.2)(1.4)	(160.2)	169.8(-2.6)
UME	18/8	TR	672.45	90.1 (0.4)			(160.2)(3.6)		188.3 (0.3)
SKA	18/8	TR	741.10	99.2 (1.2)					207.9 (0.7)
KAJ	18/8	TR	756.62	102.1 (2.2)			(176.1)(1.4)	(203.1)	214.1 (2.6)
JOE	18/8	TR	944.33	122.9 (0.9)	144.0(-0.5)	152.5(-1.7)	(217.5)(2.5)	(254.8)	271.0 (7.1)
LHN	18/8	TR	1031.39	134.7 (1.3)			(236.4)(2.7)		291.8 (3.5)
POR	18/8	TR	1104.10	143.9 (1.6)					
UPP	18/8	TR	1108.03				(251.1)(1.0)		310.1 (0.5)
KLS	18/8	TR	1524.97						429.7 (3.3)
TRO	20/8	TR	31.26			5.3 (0.0)			
KIR	20/8	TR	234.30	36.7 (0.5)					65.4(-0.1)
KEV	20/8	TR	337.27	49.5 (0.7)	54.2 (1.1)	56.5 (1.1)	82.4(-2.2)	91.1	95.5 (1.1)
SOD	20/8	TR	434.14	61.2 (0.6)	69.2 (1.5)	72.7 (1.6)	10[illegible].7 (1.2)	115.2	119.2(-2.1)
KRK	20/8	TR	454.99	64.7 (1.6)					126.8(-0.3)
OUL	20/8	TR	617.05	84.4 (1.5)	93.2(-2.0)	100.2(-0.6)	(147.0)(2.2)	152.6	171.4(-1.0)
UME	20/8	TR	672.37	90.8 (1.2)			(160.2)(3.6)		188.2 (0.2)
SKA	20/8	TR	740.99	99.2 (1.2)			(175.5)(2.2)		208.1 (1.0)
KAJ	20/8	TR	756.58	101.0 (1.1)			(175.5)(0.8)	201.5	213.0 (1.5)
JOE	20/8	TR	944.30	123.2 (0.4)	144.5 (0.0)	153.0(-1.2)	(217.5)(2.5)	250.0	267.0 (3.4)
LHN	20/8	TR	1031.48	134.7 (1.3)			(236.4)(2.7)		291.8 (3.6)
POR	20/8	TR	1104.[illegible]0	143.6 (1.2)			(251.6)(2.2)		319.6(10.9)
UPP	20/8	TR	1107.94	141.8(-0.9)					312.4 (2.8)

TABLE 3A: TRAVEL TIMES FROM THE SHOTPOINT TROMSO (TR)

STATION	DATE		DIST (KM)	PN	PB	PG	SN	SB	SG
KON	18/8	KR	202.18	31.8(-0.4)	32.4(-0.3)				56.4 (-0.1)
OOT	18/8	KR	235.2[illegible]	37.6 (1.3)					65.3 (-0.5)
BER	18/8	KR	307.38	43.3(-1.7)			77.6(-0.5)		85.7 (-0.7)
LHN	18/8	KR	373.25	52.3(-0.8)	58.8 (0.2)				102.0 (-2.3)
KLS	18/8	KR	501.03				117.6(-2.2)		(138.3)(-1.7)
UPP	18/8	KR	586.78				138.7 (0.4)		(168.0)(3.9)
SKA	18/8	KR	659.77						(183.4)(-0.4)
SPA	18/8	KR	920.50						(257.1)(-0.1)
POR	18/8	KR	1030.20	130.8(-2.4)			228.0(-5.3)		(286.[illegible])(-1.5)
KAJ	18/8	KR	1250.43	160.8 (0.7)			279.0(-1.6)	(333.2)	(357.4)(8.0)
KIR	18/8	KR	1256.27						(35[illegible].4)(1.3)
SOD	18/8	KR	1399.58						(399.4)(8.3)
KON	20/8	KR	201.77	31.8(-0.4)	32.4(-0.2)				56.4 (0.0)
OOT	20/8	KR	234.45	37.3 (1.1)					65.2 (-0.4)
BER	20/8	KR	307.77	43.5(-1.6)			76.4(-1.9)		86.3 (0.2)
LHN	20/8	KR	372.93	51.8(-1.2)	58.7 (0.2)				101.9 (-2.3)
KLS	20/8	KR	500.29			82.7 (0.8)			(137.1)(-2.7)
UPP	20/8	KR	586.07	78.7(-0.3)			138.4 (0.3)		(161.0)(-2.8)
SKA	20/8	KR	659.52						(183.1)(-1.2)
UMF	20/8	KR	919.99						(251.8)(0.7)
POR	20/8	KR	1030.40	132.6(-0.6)			2[illegible]1.1(-2.3)		
KAJ	20/8	KR	1249.83	159.2(-0.8)			279.0(-1.4)	(340.0)	(356.6)(7.2)
KIR	20/8	KR	1255.94						(355.2)(1.4)
KON	21/8	KR	202.12		2.4(-0.3)				56.4 (-0.1)
OOT	21/8	KR	235.27	38.0 (1.7)					65.4 (-0.4)
LHN	21/8	KR	373.25	52.2(-0.9)	58.8 (0.2)				101.8 (-2.5)
KLS	21/8	KR	501.03						(138.2)(-1.8)
UPP	21/8	KR	586.78	78.9(-0.2)			138.8 (0.5)		(162.1)(-1.9)
SKA	21/8	KR	659.77					--	(183.8)(-0.6)
UMF	21/8	KR	920.50						(259.0)(1.7)
NUR	21/8	KR	983.07				223.6 (0.3)		
POR	21/8	KR	1030.20	130.5(-2.7)			231.3(-2.0)		(286.[illegible])(-1.4)
KAJ	21/8	KR	1250.43	160.2 (0.1)			279.7(-0.9)		(351.7)(2.1)
KIR	21/8	KR	12[illegible]6.27						(354.2)(3.1)
SOD	21/8	KR	1399.58						(359.8)(4.7)
KON	3/9	GR	160.55	26.1(-1.0)					45.6 (0.6)
OOT	3/9	GR	206.23	33.0 (0.2)			57.8 (1.2)		
BER	3/9	GR	302.64	43.8(-0.7)					
LHN	3/9	GR	331.78	47.1(-0.9)	52.7 (0.4)		83.7 (0.1)		92.1 (-0.5)
UPP	3/9	GR	541.75	73.2(-0.4)			129.1 (0.5)		(147.6)(-3.8)
SKA	3/9	GR	620.38						(175.8)(2.4)
NUR	3/9	GR	938.22				211.3(-2.3)	(251.1)	(257.5)(-4.6)
POR	3/9	GR	985.70	127.1(-0.7)			218.6(-5.2)	(255.8)	(272.3)(-3.1)
KAJ	3/9	GR	1203.55				273.7 (3.1)	(322.6)	(346.0)(9.5)
KON 16	3/9	GR	151.79	26.1(-1.2)					45.6 (0.3)
OOT 16	3/9	GR	212.24	33.8 (0.3)					
BER 16	3/9	GR	298.25	43.4(-0.5)			76.7 (0.4)		
LHN 16	3/9	GR	333.12	47.4(-0.8)	52.7 ([illegible].2)				91.2 (-1.9)
KLS 16	3/9	GR	485.87						135.5 (-0.3)
UPP 16	3/9	GR	546.94	74.9 (0.6)			131.3 (1.6)		
SKA 16	3/9	GR	621.24						(172.5)(-1.1)
NUR 16	3/9	GR	943.45				211.3(-3.4)		(263.3)(-0.3)
POR 16	3/9	GR	991.0	152.0 (0.0)					
KAJ 16	3/9	GR	1207.56	154.1(-0.7)	183.0(-1.1)		270.0(-1.4)	(322.9)	(340.6)(3.1)
KIR 16	3/9	GR	1215.83						(347.7)(7.9)
JOE 16	3/9	GR	1251.70	157.3(-2.9)					
KON	4/9	GR	159.47	26.6(-0.4)					45.1 (0.4)
OOT	4/9	GR	211.39	33.6 (0.2)					58.7 (-0.4)
BER	4/9	GR	297.63	43.9 (0.0)					86.8 (3.5)
LHN	4/9	GR	330.80	47.2(-0.7)		52.2(-1.9)	83.6 (0.3)		91.8 (0.5)
KLS	4/9	GR	485.60				114.7(-1.7)		134.2 (-1.4)
UPP	4/9	GR	544.84				129.6 (0.3)		(149.0)(-3.2)
SKA	4/9	GR	618.98				149.0 (3.8)		(177.2)(4.2)
UMF	4/9	GR	875.13				202.4 (2.3)		(245.4)(0.8)
NUR	4/9	GR	941.35				231.8(-2.5)	(249.5)	(266.5)(3.4)
POR	4/9	GR	988.90				221.2(-[illegible].3)		
KIR	4/9	GR	1213.48						(337.7)(-1.3)
KAJ	4/9	GR	1205.19	153.5(-1.0)			269.0(-1.9)	(323.0)	(336.4)(-0.3)
JOE	4/9	GR	1249.43						(358.0)(8.9)
SOD	4/9	GR	1354.7[illegible]				304.7 (1.6)		(383.0)(4.4)

TABLE 3b. TRAVEL TIMES FROM THE SHOTPOINTS GRIKSTAD (GR) AND KRISTIANSAND (KR)

STATION	DATE		DIST(KM)	PN	PB	PG	SN	SB	SG
BER	28/8	FL	122.33		19.9(-0.8)		37.5(-1.0)		35.1 (0.5)
LHN	28/8	FL	316.89	45.9(-0.3)	49.8(-0.2)	51.5(-0.3)	82.0 (1.6)		89.0 (0.1)
KON	28/8	FL	324.28						90.0 (-0.6)
SKA	28/8	FL	439.19			71.8 (0.0)			
UPP	28/8	FL	710.14						(201.2)(2.7)
UME	28/8	FL	819.08						(232.4)(3.5)
KLS	28/8	FL	848.31						(238.3)(1.2)
KIR	28/8	FL	1015.98						(284.8)(1.0)
POR	28/8	FL	1115.50						(311.6)(0.0)
KAJ	28/8	FL	1186.05						(333.0)(-0.4)
SOD	28/8	FL	1220.30						(344.6)(3.6)
BER	29/8	FL	122.46		19.9(-0.8)		37.3(-1.2)		35.2 (0.8)
LHN	29/8	FL	317.21	46.5 (0.2)	50.5 (0.4)	52.1 (0.1)	82.0 (1.6)		88.6 (-0.1)
KON	29/8	FL	324.58		49.8(-1.3)				92.3 (1.5)
SKA	29/8	FL	439.39			70.1(-1.7)			
UPP	29/8	FL	710.46						(203.1)(4.5)
UME	29/8	FL	819.33						(231.2)
KLS	29/8	FL	848.61						(236.0)(-1.1)
KIR	29/8	FL	1015.70						(285.3)(1.4)
TUR	29/8	FL	1063.14				241.[illegible] (1.0)	(289.[illegible])	(300.2)(3.1)
POR	29/8	FL	1115.60				250.6(-1.0)	(298.3)	(314.0)(2.2)
KAJ	29/8	FL	1186.30	151.0(-1.2)			260.3(-6.5)		(339.[illegible])(7.8)
SOD	29/8	FL	1220.47	151.0(-1.2)			274.9 (0.5)		(344.5)
BER	30/8	FL	122.41		19.[illegible](-1.0)		37.4(-1.1)		34.8 (0.5)
LHN	30/8	FL	316.96	[illegible] (0.0)	49.9(-0.1)	51.7(-0.1)			88.4 (-0.2)
KON	30/8	FL	324.28		50.9(-0.2)				90.1 (-0.5)
SKA	30/8	FL	439.10			70.9(-0.9)			
UPP	30/8	FL	710.11						(201.9)(3.4)
BER	2/9	FR	55.52			9.0(-0.2)			16.8 (1.1)
KON	2/9	FR	296.93		47.6 (0.5)	50.7 (2.0)	77.3 (1.2)		
LHN	2/9	FR	328.96	47.3(-0.4)	51.5(-0.3)		81.9(-0.9)		87.9 (-[illegible])
SKA	2/9	FR	493.32						138.2 (0.3)
GOT	2/9	FR	536.53						(147.3)(-2.6)
KIR	2/9	FR	1079.70						(305.6)(3.9)
TUR	2/9	FR	1080.39				245.2 (1.0)	(289.1)	(305.5)(3.6)
POR	2/9	FR	1132.00						(325.7)(9.3)
KAJ	2/9	FR	1227.70	157.5			275.[illegible](-0.5)	(325.7)	(350.3)([illegible])
SOD	2/9	FR	1278.05						(354.9)(-2.2)
JOE	2/9	FR	1321.03					(355.1)	
BER	3/9	FR	55.5			9.1(-0.1)			15.4 (-0.7)
LHN	3/9	FR	329.02	47.2(-0.5)	51.4(-0.4)				90.5 (-1.4)
SKA	3/9	FR	439.37						
GOT	3/9	FR	536.59						(143.5)(-6.4)
KIR	3/9	FR	1079.74						(302.4)(5.7)
TUR	3/9	FR	1080.45				244.5 (0.3)	(289.0)	(305.0)(3.0)
POR	3/9	FR	1132.00					(299.0)	(325.6)([illegible])
KAJ	3/9	FR	1227.76					(325.7)	(350.1)(7.0)
SOD	3/9	FR	1278.10						(362.8)(5.6)
BER	4/9	FR	55.55			9.5(-0.2)			15.80 (0.1)
KON	4/9	FR	2[illegible].03	44.2(0.3)			76.7 (0.6)		
LHN	4/9	FR	329.01	47.4(-0.3)	51.8 (0.0)		80.9(-2.0)		90.2(-1.5)
SKA	4/9	FR	439.79						
GOT	4/9	FR	536.65						(147.2)(-2.8)
UPP	4/9	FR	713.88						(200.5)(0.9)
UME	4/9	FR	862.48						(242.4)(2.3)
KIR	4/9	FR	1079.44						(307.4)(5.7)
TUR	4/9	FR	1080.44					(275.0)	(311.1)(9.2)
POR	4/9	FR	1132.00				255.6 (0.3)		(326.5)(10.[illegible])
KAJ	4/9	FR	1227.71	136.2([illegible])			278.0 (0.2)	(323.5)	(351.0)(7.0)
SOD	4/9	FR	1278.02						(364.5)(7.4)
LHN	0/8	AB	49.02	15.2(-0.8)		11.5 (0.0)			20.2 (0.8)

TABLE 30: TRAVEL TIMES FROM THE SHOTPOINTS FLORA (FL), FRITZ (FR) AND ANNEN (AB).

Table 4:

Instrumentation and instrument constants for the seismological stations in Finland (E. Vesanen 1963), Sweden (M. Båth 1963) and Norway.

Stat.	Comp.	Type of Instrum.	Free period sec. To	Tg	Magnification at To	Damping ratio	Recording type	Drum speed mm/min	Remarks
KEV	Z	Press-Ewing	30[1]	100	750[2]		Photopaper	30	1) From June 23
	N	" "	30[1]	100	750[2]	"	" "	30	1963, T = 15
	E	" "	30[1]	100	750[2]	"	" "	30	2) From June 23
	Z	Benioff	1.0	0.75	25000	17:1	" "	60	1965 magnification
	N	"	1.0	0.75	25000	17:1	" "	60	= 1500
	E	"	1.0	0.75	25000	17:1	" "	60	
SOD	Z	Benioff	1	0.2	34000[3]	15:1	" "	60	3) Approx.
	N	Nurmia	0.5	1.1	35000[3]	3:1	" "	30	
	E	"	0.5	1.1	35000[3]	3:1	" "	30	
	Z	"	0.5	-	100000[3]	2:1	Smoked pap.	60	
	Microb.	"	-	-	-	-	" "	3	
OUL	Z	Press-Ewing	30[4]	100	750[5]		Photopaper	30	4) From June 30
	Z	Willmore	0.65	0.2	360000	4	Heat sensitive	30	1963, 15 sec.
									5) From June 30
KJN	Z	Benioff	1.0	0.75	46000	17:1	Photopaper	60	1963, 1500
	N	(port.)	1.0	0.75	46000	17:1	" "	60	
	E	"	1.0	0.75	46000	17:1	" "	60	
JOE	Z	Willmore	0.6	0.2	75000	2:1	Heat sensitive	60	
NUR	Z	Press-Ewing	30[6]	100	3000[7]		Photopaper	30	6) From June 1
	N	" "	30[6]	100	3000[7]	"	" "	30	1965 T = 15
	E	" "	30[6]	100	3000[7]	"	" "	30	7) From June 1
	Z	Benioff	1.0	0.74	25000	17:1	" "	60	1963 magnif. 1500
	N	"	1.0	0.74	25000	17:1	" "	60	
	E	"	1.0	0.74	25000	17:1	" "	60	
	ZZ	Nurmia	0.6	0.2	170000	3:1	" "	60	
	Z	"	0.5	-	-	2:1	Smoked pap.	60	
HEL	Z	Willmore	0.5	-	100000[8]	3:1	Heat sensitive	60	8) Approx.
KRK	Z	Sprengnether	15[9]	100	1500	crit.	Photopaper	30	9) From 30 to 15
	N	"	15[9]	100	1500	"	" "	30	May 1963.
	E	"	15[9]	100	1800	"	" "	30	
	Z	Benioff	1.0	0.75	25000	17:1	" "	60	
	N	"	1.0	0.75	25000	17:1	" "	60	
	E	"	1.0	0.75	25000	17:1	" "	60	
FKO	Z	Benioff	1.0	0.2	30000	-	35 mm film	15	
	N	"	1.0	0.2	30000	-	" "	15	
	E	"	1.0	0.2	30000	-	" "	15	
KON	Z	Sprengnether	15[10]	100	1500	crit.	Photopaper	30	10) From 30 to
	N	"	15[10]	100	1500	"	" "	30	15. sec May 1963
	E	"	15[10]	100	1500	"	" "	30	
	Z	Benioff	1.0	0.75	25000	17:1	" "	60	
	N	"	1.0	0.75	25000	17:1	"	60	
	E	"	1.0	0.75	25000	17:1	" "	60	
BER	Z	Wiechert	4.5	-	300	3.3	Smoked pap.	30	
	N	"	9.5	-	180	3.5	" "	15	
	E	"	9.5	-	180	3.5	" "	15	
	Z	Willmore	1.0	0.1	20000	-	Ink record	60	
	N	"	1.0	0.1	20000	-	" "	60	
	E	"	1.0	0.1	20000	-	" "	60	
LHN	Z	Benioff	1.0	0.2	125000	15:1	35 mm film	15	7 element linear
	Az 138°	"	1.0	0.2	125000	15:1	" "	15	crossed array.
	Az 228°	"	1.0	0.2	125000	15:1	" "	15	Spacing 1 km.
	Z	Sprengnether	20	30	15000	crit.	" "	3	
	Az 138°	"	20	30	15000	"	" "	3	
	Az 228°	"	20	30	15000	"	" "	3	
UPP	E	Benioff	1.0	0.7	60000				
	N	"	1.0	0.7	70000				
	Z	"	1.0	0.7	40000				
	E	"	1.0	74	2810				
	N	"	1.0	87	2600				
	Z	"	1.0	76	1660				
UPP	E	Wiechert	10.8	-	187				
	N	"	9.7	-	183				
	E	Press-Ewing	13.0	87	1860				
	N	" "	15.0	81	1370				
	Z	" "	13.0	83	1700				
	Z	" "	14.9	100	1200				
KIR	Z	Grenet-Coul.	1.4	0.7	11150				
	E	Galitzin	11.4	11.8	820				
	N	"	11.4	11.5	960				
	Z	"	7.3	11.7	660				
	Z	Press-Ewing	13	100	1200				
SKA	Z	Grenet-Coul.	1.4	0.8	14500				
GOT	Z	Grenet-Coul.	1.4	0.3	10530				
UME	E	Benioff	1.4	0.7	75000				
	N	"	1.0	0.7	75000				
	Z	"	1.0	0.7	75000				
	E	Press-Ewing	30	99.3	1500				
	N	" "	30	100	1500				
	Z	" "	30	100	1500				
KLS	Z	Grenet-Coul.	1.5	0.7	11530				

Table 5.

Shotpoint	Pn v	Pn I	Pn RMSE	Pn n	Pb v	Pb I	Pb RMSE	Pb n	Pg v	Pg I	Pg RMSE	Pg n	Sn v	Sn I	Sn RMSE	Sn n	Sg v	Sg I	Sg RMSE	Sg n
Tromsø	8.18	3.2	0.7	40									4.57	10.5	1.2	33				
Kr.sand – Oriastad	8.27	7.8	1.8	37									4.70	12.9	2.0	32				
Flora – Fedje	8.26	7.6	0.4	11									4.66	13.7	2.8	20				
Data from all shotp.	8.20	7.6	1.1	88	6.60	2.3	1.4	41	6.13	0.7	1.2	29	4.66	12.3	2.9	85	3.59	0.6	13.2	163
Δ 500 km																	3.58	0.1	2.0	59
Δ 100 km									6.13	0.2	0.1	(8)								

v = velocity (km/sec)

I = intercept time (sec)

RMSE = root mean square error

n = number of observations

Table 6:

Velocities for seismic waves obtained in Fennoscandia and the Canadian Shield (km/sec).

	Fennoscandia (The Baltic Shield).					The Canadian Shield.		
	I	II	III	IV	V	VI	VII	VIII
Pn	8.20	8.20	8.20	8.15	8.1	8.18		8.17
Px			7.39					
Pb	6.60	6.65	6.51	6.70	6.6		7.10	7.10
Pg	6.13	6.10		5.95	6.1	6.25	6.20	6.15
Sn	4.66	4.60	4.65			4.85		4.60
Sx			4.21					
Sb		3.75					3.92	4.10
Sg	3.58	3.50	3.62			3.54	3.54	3.65

I: The present study.

II: Penttilä (1965): Mean velocity based upon refraction measurements in Finland during recent years.

III: Sellevoll and Kanestrøm (1965) Earthquake study.

IV: Sellevoll and Penttilä (1964). Timed blasts.

V: Hirschleber, Hjelme and Sellevoll (1966). Timed blasts (Denmark).

VI: Hodgson (1953a). Rockburst.

VII: Hodgson (1953b). Timed blasts.

VIII: Hall and Brisbin (1961). Timed blasts.

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13. ABSTRACT

A study of a possible relocation of the seismic array station LHN (Lillehammer) in south-central Norway is first reported in Part I. One new site is recommended. Part II reports results obtained from three widely separated seismic refraction profiles in Norway and a travel time study for seismic waves in Fennoscandia. The Pn velocities found are very close to 8.20 km/sec. Indications of a phase with velocity of 7.50 km/sec are observed. A phase with a velocity of about 6.60 km/sec is well defined in the seismograms. The amplitude for this phase varies strongly. The velocity for the first direct longitudinal wave varies mostly from 6.00 km/sec to 6.15 km/sec. A crustal thickness from 31 km to 38 km has been determined.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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seismic velocities						
travel times						
crustal thickness						
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particle motion						
upper mantle						